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COMPACTION AND SOME OILFIELD FEATURES.*

By G. D. Hobson.

Some years ago Ortenblad[6] made a mathematical study of the problem of compaction in a sediment, and it seems to be of interest to apply his equations, together with certain modifications and allied considerations, to some of the oilfield features which may be connected with compaction. Qualitative and also *speculative* quantitative applications appear to be practicable, although obviously it is to the order of the latter results in most instances, rather than to the actual numerical values, that the most weight must be attached, due, among other factors, to the uncertainty concerning the degree of precision of the basic data used in the computations. However, the present deductions may lead to further calculations based on more accurate data on the physical constants of the sediments for a given set of circumstances, and also to the adduction of data concerning the various oilfield features to support, supplement, or contradict the deductions.

Definition of Symbols.

w = hydrodynamic pressure, the pressure causing flow of the compaction fluids (gm./cm.^{2}).

p = intergranular pressure (gm./cm.^{2}).

h = reduced thickness of the compacting series, *i.e.* the thickness when the porosity is zero.

z = reduced height of a point, measured from the base of the compacting series.

γ = the apparent density in water of the sedimenting grains, *i.e.* the true density minus 1. Here γ is given the value of 1·7.

q = the rate of sedimentation expressed in grams weight in water/sq. cm./year.

$a = -\frac{dp}{dc}$ = the modulus of compression.

k = permeability of the sediment (cm./year).

$c = \frac{k}{a}$. Terzaghi's experiments[9] showed c to be practically constant, and here constancy is assumed unless otherwise stated.

e = base of Napierian logarithms.

$b = \frac{q}{\gamma c} = \frac{qa}{\gamma k}$.

H = true thickness of the deposit.

T = time, in years, which has elapsed since the cessation of deposition.

P = average porosity of the surface sediments, expressed as a fraction.

ϵ = the voids ratio—the ratio between the volume of voids and the volume of solid matter.

The significance of other symbols is explained where they are first employed.

* Received 8th January, 1943.

Some of the Factors Involved in the Compaction Process.

In his mathematical investigation of the compaction process, Ortenblad dealt with a deposit of uniform grain-size range, laid down at a constant rate, and he also examined cases where a more permeable or a less permeable layer was incorporated, or where there was a load of more permeable sediment. He discussed two stages in the compaction process : (*a*) a stage during which sediment is being deposited, and (*b*) an ensuing stage during which compaction continues without further deposition. It was assumed, in formulating the basic equations, (1) that the permeability is constant, and (2) that it is a function of the degree of compaction. After investigating the first stage according to each of these assumptions, Ortenblad found, to his own surprise, that for the example which he examined numerically on the basis of his equations, the results were not significantly different, and he therefore concluded that the same would probably be true for the second stage. Consequently, he did not attempt to solve the differential equations for the second stage, using the assumption of changing permeability, and these equations seem likely to be soluble only with difficulty, if at all. It must be noted, however, that the thickness of the deposit in his numerical example was only 50 m.

In Ortenblad's investigation the water was assumed to be expressed by viscous flow alone, and no allowance was made for the change of the viscosity of water with depth of burial as a result of the increase in temperature and pressure. This was fully justifiable in the examples which he worked out numerically.

At temperatures below 30° C. the viscosity of water decreases with increased pressure up to about 1000 atmospheres, and increases thereafter, but above 30° C. there is a continuous increase of viscosity with increased pressure. The viscosity decreases with rise in temperature at a given pressure, and altogether it would appear that the viscosity of water will decrease continuously with increased depth of burial, due to the combined effects of rising temperature and pressure at small depths, and to the probable domination of the pressure factor by the temperature factor at greater depths.* The same remarks probably hold true for the saline waters which are likely to be present in the sediments. This decrease in viscosity is equivalent to an increase in permeability, thereby rendering Ortenblad's first assumption regarding permeability, in effect, more nearly correct than it would be otherwise. It is possible, however, that in very fine pores the viscosity of water may differ from the value for water in bulk. Terzaghi believes that the viscosity is higher in fine pores,† and his

* Hubbert's calculations (*J. Geol.*, 1940, **48**, (8), 785) on the effect of depth of burial on the viscosity of water give the viscosity at a depth of 3000 m. as 0·284 centipoises if the viscosity at a temperature of 10° C. at the surface is 1·308 centipoises.

† In a stable paste under a pressure of 8 kg./cm.^{2} the water films associated with clay particles may be about 3×10^{-6} cm. thick (F. H. Norton and F. B. Hodgdon, *J. Amer. Ceram. Soc.*, 1932, **15**, 191), and Houwink [" Elasticity, Plasticity, and Structure of Matter " (Cambridge University Press, 1937)] considers that the viscosity of water in these films may be normal. He quotes experiments by Bowden and Bastow (*Nature*, 1935, **135**, 828) on the flow of water between *glass* plates about 10^{-6} cm. apart, in which experiments the viscosity of the water was the same as that of water in bulk. This separation is of the same order as the maximum separation at which the viscosity increase begins to be appreciable according to Terzaghi's equations.

equations,[11] one of the attempts to express this difference quantitatively, give

$$v_0' = v_0\left(1 + \frac{6{\cdot}02 \times 10^{-42}}{s^8}\right) \text{ to } v_0\left(1 + \frac{2{\cdot}42 \times 10^{-43}}{s^8}\right)$$

[v_0 = normal viscosity of water; v_0' = viscosity of water in a slit $2s$ cm. in width] and show no appreciable increase in viscosity until s becomes about 0·00001 cm., but the viscosity increases very quickly for smaller values of s, being $4{\cdot}58v_0$ for $s = 0{\cdot}000006$ cm. If there is a viscosity increase of this nature it may affect the results considerably, for it would reduce the rate of loss of water, and so cause the porosity to be high, and at the same time it would defer the date at which compaction ceased.

The loss of water in the later stages of compaction may be wholly or largely by processes other than normal viscous flow, probably including the taking up of water in hydration or mineral transformation, which may make the pressure decay and compaction more rapid than might otherwise be the case, except in so far as a possible concomitant reduction in pore volume, by increase in size of the grains, hinders the passage of free water through the pores.

The conditions obtaining during the formation and compaction of any considerable thickness of sediments such as occur in oilfields are much more complicated than was assumed in Ortenblad's investigation, for there is usually an alternation of coarse and fine beds (highly permeable and less permeable beds); the rates of sedimentation may vary even during the deposition of a relatively thin section; there may be periods of non-deposition or erosion; the beds may not be of uniform thickness, and lateral variation or tilting may provide paths for fluid exit which markedly disturb the general vertical flow in some localities; the surface on which deposition starts may be irregular and/or permeable, and folding may take place. Furthermore, there are indications that even in a seemingly fairly uniform mass of compacting beds, the water movement may be concentrated to some extent at certain points,[7] rather than be uniformly distributed. Nevertheless, it is probably of value to note the broader inferences to be drawn from Ortenblad's final equations, inferences which agree with conclusions reached without recourse to rigid mathematical analysis.

General Inferences from Ortenblad's Equations.

(1) For sediments of identical grain size, but for different rates of sedimentation, those being laid down most slowly will be most compact.

(2) After sedimentation ceases the hydrodynamic pressure at a given point, *i.e.* the pressure component driving liquid from the sediment, and also the porosity at that point decrease with time, comparatively rapidly at first, and then more and more slowly. As the hydrodynamic pressure decreases the intergranular pressure increases correspondingly.

(3) At a given reduced depth the porosity in a thick deposit will be greater than at the same depth in a thinner deposit, until compaction ceases.

Hence, it seems likely that unless compaction is complete soon, in geological terms, as assumed by Hedberg, a single depth-porosity relationship cannot be expected if the ages, thicknesses, and rates of sedimentation

of the series differ, even though they may be identical in all other respects. The older and/or more slowly deposited or thinner series will be the more compact.

Reservoir Pressures.

For the base of a deposit Ortenblad's equations give :

$$w = \gamma h - \frac{\gamma}{b}\left(1 - \frac{1}{e^{bh}}\right)$$

when sedimentation is just complete. Therefore, as the permeability approaches zero, the hydrodynamic pressure, w, will approach, by increasing, the ultimate value of γh. Consequently, the maximum pressure attainable at the base of a compactible series is $\gamma h + H$, the density of water being taken as unity. Thus the theoretical maximum pressure attainable is somewhat greater than the weight of the rock solid, for that is $h(\gamma + 1) = \gamma h + h$, and since $H > h$, $\gamma h + H > \gamma h + h$.

Similarly, as h increases, or as the rate of sedimentation increases, w again approaches the limiting value of γh. Since the ratio $\frac{H}{h}$ decreases as h increases, the relative excess of the actual pressure over the rock weight decreases, *i.e.* $\frac{\gamma h + H}{\gamma h + h}$ approaches unity by decreasing.

Table I.

Hydrodynamic Pressure and the Rate of Sedimentation.

$a = 0{\cdot}00024$ cm.^{2}/gm.; $k = 0{\cdot}25$ cm./yr.; $h = 5880$ m.

	Rate of sedimentation 0·2 gm./cm.^{2}/yr. 5,000,000 years of sedimentation.	Rate of sedimentation 0·02 gm./cm.^{2}/yr. 50,000,000 years of sedimentation.
w—hydrodynamic pressure at end of sedimentation . .	985 kg./cm.^{2}	850 kg./cm.^{2}

Table II.

Hydrodynamic Pressure and Compressibility or Variation in c.

$q = 0{\cdot}02$ gm./cm.^{2}; $k = 0{\cdot}25$ cm./yr.; $h = 588$ m.

Compressibility a.	$c = \frac{k}{a}$.	Hydrodynamic pressure.
0·00012 cm.^{2}/gm.	2083	15 kg./cm.^{2}
0·00048 ,,	521	45 ,,
0·00192 ,,	130	81 ,,

Ortenblad's equation for the hydrodynamic pressure after any period T subsequent to the commencement of the second stage of compaction is approximately :

$$w = \frac{16\gamma h^2 b}{\pi} \cdot \frac{\frac{2hb}{\pi} + e^{-bh}}{4h^2b^2 + \pi^2} \cdot e^{-\frac{c\pi^2}{4h^2}T} \cdot \sin\frac{\pi}{2h}(h - z)$$

This is the first term of a rapidly converging series, and for the base of the deposit it reduces to :

$$w = \frac{16\gamma h^2 b}{\pi} \cdot \frac{\frac{2hb}{\pi} + e^{-hh}}{4h^2b^2 + \pi^2} \cdot e^{-\frac{c\pi^2}{4h^2}T}$$

w decreases exponentially for a given deposit as T increases, and the above equation may be re-written as $w = Xe^{-KT}$, where

$$X = \frac{16\gamma h^2 b}{\pi} \cdot \frac{\frac{2hb}{\pi} + e^{-hh}}{4h^2b^2 + \pi^2} \text{ and } K = \frac{c\pi^2}{4h^2}.$$

The more accurate relationship for w may be written in a contracted form as :

$$w = X_1e^{-KT} + X_2e^{-9KT} + X_3e^{-25KT} + \ldots$$

so that w, the hydrodynamic pressure, is the sum of a series of terms which decrease exponentially as the time, T, increases.

TABLE III.*

The Decay of the Hydrodynamic Pressure at the Base of a Sedimentary Series after the Cessation of Deposition.

$a = 0{\cdot}00024$ cm.^{2}/gm.; $q = 0{\cdot}02$ gm./cm.^{2}/yr.

Number of years since end of deposition.	Hydrodynamic pressure.			
	Permeability 0·25 cm./yr.		Permeability 0·025 cm./yr.	
	5,000,000 yr. of deposition.	50,000,000 yr. of deposition.	5,000,000 yr. of deposition.	50,000,000 yr. of deposition.
0	27 kg./cm.^{2}	770 kg./cm.^{2}	77 kg./cm.^{2}	810 kg./cm.^{2}
5,000,000	0·7 ,,	—	53 ,,	—
10,000,000	0·02 ,,	—	—	—
50,000,000	—	530 ,,	1·9 ,,	780 ,,
100,000,000	—	—	0·05 ,,	—
150,000,000	—	120 ,,	—	730 ,,
500,000,000	—	—	—	560 ,,
Reduced thickness	588 m.	5880 m.	588 m.	5880 m.

* The hydrodynamic pressures given in Table III were computed by means of the approximate relationship : $w = Xe^{-KT}$. Consequently the values are lower than would have been obtained by using the more accurate relationship : $w = X_1e^{-KT} + X_2e^{-9KT} + X_3e^{-25KT} + \ldots$. The hydrodynamic pressure when sedimentation is just complete ($k = 0{\cdot}25$ cm./yr.; $q = 0{\cdot}02$ gm./cm.^{2}/yr.; $h = 5880$ m.) is given as 770 kg./cm.^{2} in Table III, whereas the hydrodynamic pressure calculated for the same conditions using the relationship $w = \gamma h - \frac{\gamma}{b}\left(1 - \frac{1}{e^{hh}}\right)$, is 850 kg./cm.^{2} (Table I). However, when the first five terms of the relationship $w = X_1e^{-KT} + X_2e^{-9KT} + X_3e^{-25KT} + \ldots$ are used in the calculation, the hydrodynamic pressure is found to be 852 kg./cm.^{2}.

The pressures shown in Table III are the amounts by which the pressures at the base of the deposits (thickness listed) may exceed the hydrostatic head at the dates given.

The rate of deposition assumed in the computations for Table III is higher than some of the figures quoted by Holmes,[3] but it is approximately that given by Jones[4] for a Cambrian shale sequence. The value of a is that employed by Ortenblad, whereas lower values of k than those used by Ortenblad were selected. Terzaghi's figures[10] for the permeability of clays at low liquid contents ranged from zero up to about 0·5 cm./year.

It is clear from Table III that even if Ortenblad's equation is only an approximation to the truth, there is a strong possibility that the pressures in the fluids deep down in a thick sedimentary series may be considerably in excess of hydrostatic, in spite of the fact that a long period of time may have elapsed since sedimentation ceased. For a sedimentary sequence 5880 m. in reduced thickness the hydrostatic pressure will exceed 588 kg./cm.^{2}, so that even after the lapse of 50,000,000 years, the pressure in the fluids at the base of a relatively highly permeable series may be of the order of 50% or more above hydrostatic.

GEOLOGICAL TIME SCALE (Moore[5]).

Pleistocene	2×10^6 years	Triassic	185×10^6 years
Pliocene	—	Permian	223 ,,
Miocene	—	Carboniferous	309 ,,
Oligocene	—	Devonian	354 ,,
Eocene	60×10^6 years	Silurian	381 ,,
Cretaceous	125 ,,	Ordovician	448 ,,
Jurassic	157 ,,	Cambrian	553 ,,

EFFECT ON HYDRODYNAMIC PRESSURE OF CHANGE IN PERMEABILITY WITH DEPTH.

If the permeability, k, instead of being constant, is simply related to the reduced depth, it is of interest to modify Ortenblad's differential equations accordingly, and then to obtain an expression for the intergranular pressure, from which the hydrodynamic pressure may be deduced, since $w = \gamma h - p$.

When k is variable, the fundamental differential equation is as follows:

$$\frac{\partial p}{\partial t} = -c\frac{\partial^2 w}{\partial z^2} - \frac{1}{a}\frac{\partial k}{\partial z}\cdot\frac{\partial w}{\partial z}.$$

Ortenblad obtained an approximate solution for this equation when $a = \dfrac{\alpha}{p+\beta}$ and $\dfrac{k}{a} = c$ (α and β are constants determined by experiment),[8,9] but the final equation, involving p implicitly, is rather formidable.

(*a*) Suppose that an exponential relationship holds between the permeability and the reduced depth, so that $k_z = ke^{nz}$, where n is a constant and k_z, k and z are respectively the permeability at a given point, the permeability at the base of the deposit, and the reduced distance of the given point

above the base. On appropriately modifying the fundamental differential equation, solving and introducing the boundary conditions (that $p = 0$ when $z = h$, and that $\frac{dw}{dz} = 0$ and $\frac{dp}{dz} = -\gamma$ when $z = 0$), the following relationship was obtained :

$$p = \frac{\gamma^2 nc}{q + \gamma nc}(h - z) - \frac{q\gamma^2 c}{(q + \gamma nc)^2}\left[e^{-h\left(\frac{q+\gamma nc}{\gamma c}\right)} - e^{-z\left(\frac{q+\gamma nc}{\gamma}\right)}\right],$$

which reduces to :

$$p = \frac{\gamma^2 nch}{q + \gamma nc} - \frac{q\gamma^2 c}{(q + \gamma nc)^2}\left[e^{-h\left(\frac{q+\gamma nc}{\gamma c}\right)} - 1\right]$$

for the base of the deposit (p is the intergranular pressure when deposition is just complete).

(*b*) In the case where there is a linear relationship between permeability and reduced depth, *i.e.* $k_z = k(1 + mz)$, m being a constant and k_z, k and z having the same meanings as before, it has not yet been possible to solve the resulting differential equation.

The permeability relationships suggested in (*a*) and (*b*) are, of course, merely assumptions which conform to the actual state of affairs in so far as they indicate a decrease in permeability with increased depth, but there does not appear to be any evidence as to which supposition is the more nearly correct.

Let q be 0·02 gm./cm.^{2}/year, a 0·00024 cm.^{5}/gm., and let the permeability at the top and bottom of the deposit when sedimentation ceases, be (1) 0·458 and 0·042 cm./year, (2) 0·429 and 0·071 cm./year and (3) 0·26 and 0·24 cm./year; in each case the arithmetic mean value is 0·25 cm./year. Table IV gives the values of the hydrodynamic pressure, w, computed from the above data by means of the relationship developed in (*a*), as well as values calculated by Ortenblad's equations in which k is constant and equal to 0·25 cm./year, the first equation covering the first stage of compaction, and zero time being substituted in the second equation which refers to the second stage of compaction.

TABLE IV.

h = 588 m. (*i.e.* sedimentation proceeded for 5,000,000 years).

Equation used in calculation.	Law governing value of permeability.	Permeability.		Mean value of permeability	Hydrodynamic pressure
		z = 0m.	z = hm.	when sedimentation is just complete.	
		cm./yr.	cm./yr.	cm./yr.	kg./cm.^{2}
Equation derived in (*a*)	Exponential relationship between permeability and reduced depth.	0·042	0·458	0·25	15·0
		0·071	0·429	0·25	16·9
		0·24	0·26	0·25	26·3
$w = \gamma h - \frac{\gamma}{b}\left(1 - \frac{1}{e^{bh}}\right)$	k constant	0·25	0·25	0·25	27·0,
$w = \frac{16\gamma h^2 b}{\pi} \cdot \frac{\frac{2h}{\pi} + e^{-bh}}{4h^2b^2 + \pi^2} \cdot e^{-\frac{c\pi^2}{4h^2}T}$ when $T = 0$.	k constant	0·25	0·25	0·25	27·3

It would be preferable to extend the modifications suggested in (*a*) and (*b*) to the second stage of compaction, although in the absence of such an extension it seems reasonable to assume that there will be an exponential hydrodynamic pressure decay as has already been indicated by Ortenblad's equation based on the simple assumption that the permeability is constant.

The Direction of Fluid Movement in Complex Sedimentary Deposits, and Abnormally High Pressures.

In the preceding discussion a uniform deposit with the compaction fluids flowing vertically upwards has alone been considered. Generally the sedimentary sequence is more complex, and while the same mechanisms are operative, the direction of fluid flow may be other than vertical, or even upwards in parts, leading to hydrodynamic pressures and degrees of compaction different from those predicted for a uniform deposit.

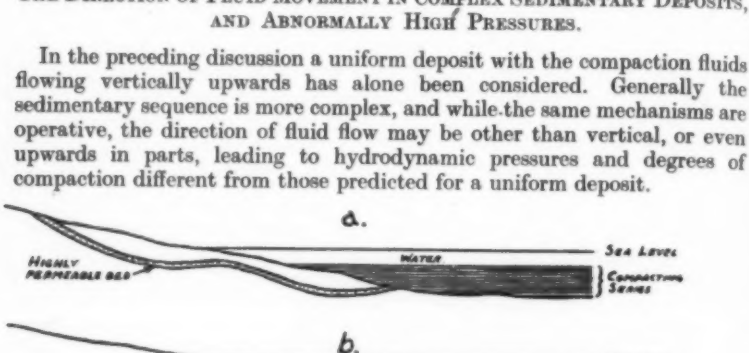

Fig. 1.

The possible considerable excess of fluid pressure above that corresponding with hydrostatic is of importance in a number of connections. If a highly permeable bed outcrops on the surface on which the compactible sediment is being laid down, and if it also outcrops on the land surface (Fig. 1*a*), it may act as a channel through which water passes into the sediment at first (*cf.* submarine springs), and that water, seeping upwards, may reduce the rate of compaction in the zone of sediment overlying the area where water is escaping from the highly permeable bed.*

According to Ortenblad, experiment shows that $\varepsilon = -\alpha' \log_e (p + p_1)$

* Burt (*J. Geol.*, 1927, **35** (7), 663) has noted that quicksands are supersaturated with water, the excess water being largely expressible by pressure, and both Burt and Gow (*Canad. Eng.*, 1920, **39**, 392) have observed that some, at least, of the quicksands, are intimately associated with springs. It seems possible that the upward flowing water could be derived either from a compacting clay or from a highly permeable water-transmitting bed which outcrops on the base of the quicksand.

$-\beta'(p+p_1)+C$, or approximately $\epsilon = -\alpha \log_e (p+\beta)+C$, since β' is very small[8]. But $p = \gamma h - w$. Therefore, $\epsilon = -\alpha \log_e (\gamma h - w + \beta) + C$. Consequently, if the hydrodynamic pressure, w, is large, $\alpha \log_e (\gamma h - w + \beta)$ will be small, and ϵ, the voids ratio, will be large.

At first the hydrodynamic pressure will be high, since it will be determined largely by the height above sea level of the land outcrop of the highly permeable bed. The high hydrodynamic pressure will hinder compaction, causing the porosity of the sediment to be higher than would be the case in the absence of the highly permeable bed. However, as the thickness of the sediment increases (at the same time the land outcrop of the highly permeable bed may be expected to have been reduced in elevation by erosion), the hydrodynamic pressure, as influenced by the weight of the compacting sediment, may become of such a magnitude as to reverse the direction of fluid flow, and fluid from the lower part of the sediment may, instead of passing upwards through the sediment, flow downwards into the highly permeable bed (*cf.* possible explanations of some unconformity oil accumulations). It seems possible that when this phase of the process has been in action for some time, the porosity of the region of the compactible bed affected by it will be less than it would have been if the reversal of flow had not taken place. This statement naturally refers to the state of affairs before compaction ceases entirely.

Highly permeable beds which do not outcrop on the land surface and which are within or below the compacting series (Fig. 1*b*) may provide conditions suitable for fluid movement similar to the second phase noted above, provided that there are differences in the thickness of the compacting beds over parts of the highly permeable bed, due to inclination of the latter or to a non-horizontal surface of the compacting sediment.

Consider two points, A and B (Fig. 1*c*), at different depths in a compactible series. Then, if B is the shallower, the hydrodynamic pressure at B will be less than that at A; it will be equal to that at B' vertically above A, if B' is at the same level as B. However, if B and A are connected by a path of high permeability—a sand—the hydrodynamic pressure required to drive water from A to B at any rate which is likely to obtain, will be less than the difference in hydrodynamic pressure between A and B', even though the distance AB may be much greater than the distance AB'. On this account, where a highly permeable connection exists between A and B, the hydrodynamic pressure at B may be substantially in excess of the value to be expected from B's depth of burial.

Two important points arise from the above conception: (1) The state of compaction in the zone of sediment overlying B will, for a time, be less than it would be in the absence of the highly permeable connection, while at points overlying those where liquid is entering the highly permeable bed, the state of compaction, especially in the lower part, though the whole zone of the compactible bed above will be affected, will temporarily be higher than it would otherwise be. (2) If there is a considerable difference in level between A and B, and the connecting bed has a high permeability yet comparatively little fluid to transmit, the hydrodynamic pressure at B may be little less than at A, and altogether the pressure at B will appear anomalous with regard to B's depth. The presence of the highly permeable

connection will, on the other hand, reduce the hydrodynamic pressures at *A* and *B'* to some extent.

If the upper part of the highly permeable bed becomes filled with oil and gas, the point *C* (Fig. 1*d*) at which the water leaves it to escape upwards will gradually become lower as oil and gas accumulate.* *C* will be at the oil–water contact zone, provided that the oil and gas zone does not contain connate water-filled patches capable of transmitting much water. Thus the region where the rate of compaction is temporarily reduced by abnormal hydrodynamic pressures will tend to overlie the oil–water contact zone (*cf.* 'haloes' in geochemical prospecting). As *C* moves downwards, compaction above *B*, *i.e.* above the oil and gas zone, will be accelerated, since the only water which will have to be transmitted will be that derived in the main from the section overlying *B*.

It is obvious that fluids will enter the highly permeable bed at all points which will give an advantageous relationship as regards hydrodynamic pressures.†

Orogenic stresses, in so far as they affect the pressures in the fluids in the sediments, can be considered as equivalent to deeper burial. Hence the hydrodynamic pressure will be in excess of that appropriate to the depth of burial of the point in question and to the ordinary loading compaction considerations. Nevertheless, the hydrodynamic pressure decay with time may still be expected to obey an exponential law, although the decay rate may possibly be somewhat greater than for the pure sedimentation-compaction process, as the thickness of sediment that the water has to traverse is less than would correspond with the porosity, permeability, and hydrodynamic relationships in a series involving pure sedimentation-compaction alone and having the same hydrodynamic pressure.

The foregoing concepts regarding the direction of fluid movement in a non-uniform sedimentary series are by no means new, but they have generally been described without adequate reference to the differences of hydrodynamic pressure which provide the motive power.

Deductions from Depth–Porosity Curves.

If a depth-porosity relationship for a sedimentary series is known from measurements, or assumed, a true depth–reduced depth curve can be

* The coarse-fine interface (V. C. Illing, *J. Inst. Pet. Tech.*, 1933, **19**, 229–260; 1939, **25**, 201) prevents the passage of the oil and gas by bulk flow from the highly permeable reservoir bed into the adjacent more fine-grained beds, until the pressure differential between these fluids and the water in the fine-grained beds has built up to a critical value which depends on the pore sizes of the two adjacent beds, and on the interfacial tension of the oil and gas against the connate water in the sediments.

† When a well is drilled into a deeply buried clay in which the hydrodynamic pressure in the contained water is high, and which still has a high porosity, an easy path is provided for the escape of some of the water in the clay immediately around the well. The rate of water escape in this manner will be small, and the effects of this escape are not likely to be readily observable. However, if the well penetrates a highly permeable bed just above or just below the clay, opportunities are presented for the easy escape of water from the clay into the highly permeable bed over a large area, and for a corresponding flow of water from the highly permeable bed into the well, because of the increased pressure drop between the clay and the highly permeable bed which generally arises as a consequence of the presence of the well. In such circumstances accelerated compaction of the clay may become possible, and the effects of this may be noticeable.

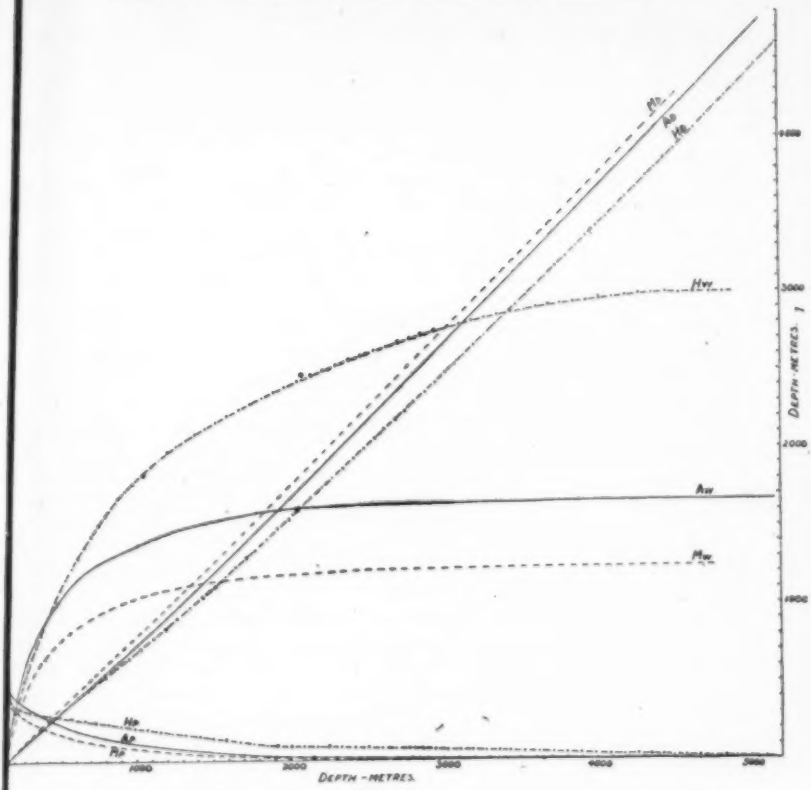

FIG. 2.

AP, *HP* AND *MP* ARE CURVES OF POROSITY PLOTTED AGAINST TRUE DEPTH. *AD*, *HD* AND *MD* ARE CURVES OF REDUCED DEPTH PLOTTED AGAINST TRUE DEPTH. *AW*, *HW* AND *MW* ARE CURVES OF THE VOLUME OF WATER IN A 1 CM.^{3} PRISM PLOTTED AGAINST THE REDUCED DEPTH. *A* INDICATES THAT THE SEDIMENT OBEYS ATHY'S COMPACTION LAW, *H* THAT IT OBEYS HEDBERG'S LAW, AND *M* THAT THE SEDIMENT HAS 30% OF NON-COMPACTIBLE BEDS, THE COMPACTIBLE BEDS OBEYING ATHY'S LAW.

constructed, for the reduced depth is simply the amount of solid matter of zero porosity down to the depth considered. Using Athy's equation[1] the reduced depth is

$$\int_0^H (1 - Pe^{-yH})dH = H + \frac{P}{y}(e^{-yH} - 1)$$

where y is a constant for a given series. Hedberg's equation[2] is a discontinuous function, which, if used to compute the reduced depth numerically, must be integrated between the limits proper to the various stages.*

* Both Athy's and Hedberg's equations and observations are open to criticism, but the experimental and observational difficulties associated with the determination of a porosity-depth relationship are of considerable magnitude.

Alternatively, the true depth–reduced depth curve can readily be obtained graphically from the porosity–depth curve (Fig. 2, A_P, H_P, or M_P) without knowing the equation of the latter, for the reduced depth corresponding with a given true depth is the area bounded by the ordinates through zero and the depth in question, and by the curve and a horizontal line through the 100 per cent. porosity point.

With the aid of the reduced depth–true depth curves (Fig. 2, A_D, H_D, and M_D) it is possible approximately to determine the volume of water expressed from a given section or passing through a given plane as the depth of burial increases. The assumption made in the latter case is that the direction of water-flow is upwards. Assumptions are also implied regarding the uniformity of the material, *i.e.* that all the compactible sections had the same porosity initially, and regarding the load and resistance attributable to the non-compactible sections (commonly sands or sandstones will be present, for an unbroken, uniform clay or shale section is unlikely to extend for any great thickness), but it does not seem that any uncertainty present in these assumptions will prevent the determination of the correct order of the quantities.

For many purposes the compactible section may be deemed to be limited to that section which is above a major unconformity. Failure to allow for compaction in the beds below the unconformity may make the amount of liquid calculated to have passed upwards through a given plane too small, whereas the lateral or downward movement of liquid makes the calculated value too high or even too low locally.

Athy's and Hedberg's relationships, being based on observations on actual sediments which undoubtedly embrace cases where highly permeable beds are involved, merely consider the loss of liquid without specifying the way in which it is lost. Thus the relationships cover loss by a general diffuse movement of liquid upwards through the sediment of low permeability, as well as by relatively concentrated flow through highly permeable beds. Deductions concerning the state of compaction will not be markedly affected by the dominance of water loss by diffuse movement, or by concentrated movement, but the amount of water flowing through a given cross-section will be largely dependent on local conditions. It is not possible readily to make satisfactory allowances for such local conditions—the presence or absence of a highly permeable bed or other disturbing influence—and so the figures calculated for the volume of water flowing upwards across a given horizontal plane merely constitute a general average which will be exceeded in the vicinity of highly permeable beds, and not attained where they are lacking. The proportional decrease in the rate of flow with increased depth of burial may be similar in the two cases, with the possibility that a rather greater proportion of the out-flowing water may travel by way of the highly permeable bed as compaction proceeds.

(1) *The Time of Oil Formation and Primary Migration.*—One of the most debated points in petroleum geology is the time of oil formation. Some maintain that oil must be formed soon after the sediments are laid down, otherwise they find it difficult to visualize a way in which the oil can be transferred from the fine-grained source rock (low permeability) to the coarser reservoir rock (high permeability). Others claim that oil formation occurs long after burial of the parent organic matter through the agency of

rise in temperature and pressure resulting from the large rock load on it. The holders of the former view look to the water expressed during compaction, which is naturally greatest in bulk and moving most quickly during the early stages of compaction, to carry oil from the source to the reservoir rock, whereas those who hold the latter view must believe that other processes are capable of accomplishing this transfer, or at least that the amount and rate of fluid flow quite late in the compaction process are sufficient to cater for primary migration. It is, therefore, interesting to estimate what quantity of water may be expected to pass into a given section from older beds for a known depth of burial, and so be available, together with water expressed by contraction of the section itself, for flushing out oil formed in the section. A number of variable factors must be considered : the thickness and characteristics of the source series, its distance above a major unconformity (the beds below the unconformity being assumed to be completely compacted), and the depth of burial (time) at which oil formation takes place.

The estimation is most easily made for a series which obeys Athy's, Hedberg's, or some other one law throughout, although it is probably preferable to consider a series more like those encountered in oilfields, with 20 or 30 per cent. of non-compactible beds in it. A curve relating reduced and true depth can be deduced for a given percentage of non-compactible beds, the compactible beds being assumed to obey a definite law, and the load–depth relationship being assumed not to be materially changed by the presence of the non-compactible beds. In order to avoid making assumptions, which would be of very limited use, about the actual distribution of the non-compactible and compactible beds, it seems best to assume that the same ratio of the two types of beds exists at all depths, which is probably a sufficiently good approximation when the alternation of the beds is frequent.

Curve M_D of Fig. 2 was prepared for a case where the ratio of the volume of solid, which when mixed with water was compactible, to the volume of non-compactible sediment (solid plus water) was 70 : 30. The compactible part was assumed to obey Athy's law.

The amount of water in a 1-cm.^{2} prism extending down to some stated depth is shown by the difference true depth minus reduced depth corresponding with the depth considered, and the values thus derived are most useful when plotted against the reduced depth (Fig. 2, curves A_W, H_W, and M_W).

Suppose that the source bed is 100 m. thick when its deposition is just complete, that its base is then 1000 m. above a major unconformity, and that the beds obey Athy's compaction law ($P = 0{\cdot}48$ and $y = 0{\cdot}00143$ in Fig. 2). When the deposition of the source bed is just complete, its reduced thickness, read from the reduced depth–true depth curve, is 54 m., and its water content is 4·6 litres in a 1-cm.^{2} prism. The reduced depth of the 1100 m. of beds (source bed 100 m. + 1000 m. of beds below) down to the unconformity is 835 m., with the consequence that the reduced thickness of the beds underlying the source bed is $835 - 54 = 781$ m., and the water content of the beds below the source rock is $(110{,}000 - 83{,}500) - (10{,}000 - 5{,}400) = 26{,}500 - 4{,}600$ cc. $= 21{\cdot}9$ litres.

When the top of the source rock is buried to 500 m. true depth, the source bed itself extends from 328 m. reduced depth, corresponding with

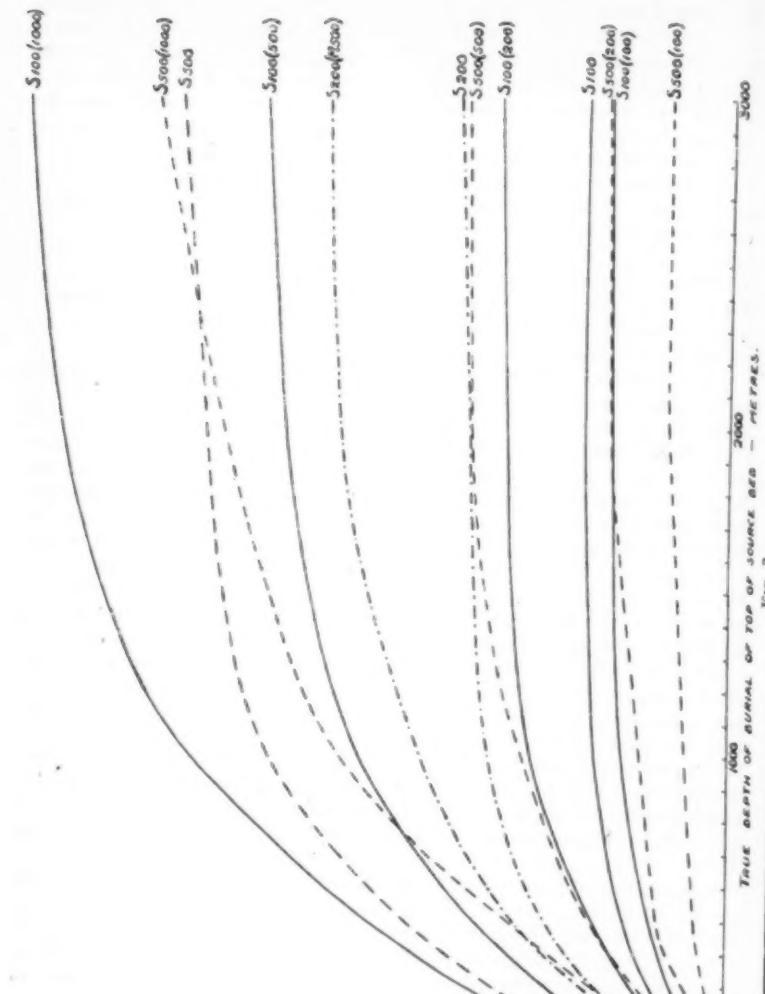
S100(1000)
S500(400)
S500
S100(500)
S100(250)
S200
S500(100)
S100(200)
S100
S500(200)
S100(100)
S500(100)
0
1000
2000
3000
TRUE DEPTH OF BURIAL OF TOP OF SOURCE BED - METRES.
0
10
20
VOLUME OF WATER EXPRESSED FROM 1·33 CM. PRISM OF SEDIMENT - LITRES.

FIG. 3.

500 m. true depth, to 382 m. reduced depth, and the beds beneath it extend from 382 m. to 1163 m. reduced depth, *i.e.* 382 + 781 m. At this stage the amount of water remaining in the source bed is (56,900 − 38,200) − (50,000 − 32,800) = 18,700 − 17,200 cc. = 1·5 litres; and the water remaining in the beds below the source bed is (146,000 − 116,300) − (56,900 − 38,200) = 29,700 − 18,700 cc. = 11·0 litres. Therefore, by the time that the source rock has been buried 500 m. deep, it has lost 4·6 − 1·5 = 3·1 litres of water per 1-cm.^{2} prism, and 21·9 − 11·0 = 10·9 litres of water per cm.^{2} will have entered its base from the underlying beds, *i.e.* 10·9 + 3·1 = 14·0 litres of water per cm.^{2} will have left the top of the source bed. In this way estimates can be made for different sets of conditions, either directly from the reduced depth–true depth curve or with the additional assistance of a water content–reduced depth curve.

The curves of Fig. 3 show the amounts of water lost from a 1-cm.^{2} prism of the source bed or of the underlying beds for different depths of burial, thicknesses of source bed and thicknesses of beds between the source bed and a major unconformity. The steepness of the curves is a measure of the rate at which water was being lost. The curves, based on Athy's data, show that for the series of combinations of circumstances selected, a substantial part of the compaction fluids passes into and through the source rock relatively early. Indeed, 75 per cent. of the possible compaction fluids has passed before the top of the source bed has been buried 1500 m. (true depth). This figure is more than 75 per cent. of the volume of the fluids likely to pass. In some cases 75 per cent. of the fluids has passed during burial to 750 m. only.

The volumes of liquid computed for a given set of circumstances vary with the compaction law employed, but the general indications are similar for Athy's and Hedberg's laws, and for the case where a proportion of non-compactible beds is included in the sedimentary series.

Estimates can also be made of the rate of flow of the water expressed in compaction, again making use of the depth–porosity curves and curves derived therefrom. The curves of Fig. 3 may be replotted with reduced depth instead of true depth as abscissae (Fig. 4, curves *A* and *B*. These are for the case of 100 m. of source bed, the base of which was 500 m. above a major unconformity when deposition of the source rock was just complete. *A* shows the water expelled from the beds below the source rock; *B* shows the total water expelled from the source rock and the beds below). If it is assumed that the bulk of the compaction took place during the time when sedimentation was proceeding, that the rate of deposition of the beds

FIG. 3.

FIG. 3.

CURVES S100, S200 AND S500 REPRESENT THE VOLUME OF LIQUID EXPRESSED FROM SOURCE ROCK SECTIONS, WHICH WERE RESPECTIVELY 100, 200 AND 500 M. THICK AS DEPOSITED, WHEN THEY ARE BURIED TO THE DEPTHS SHOWN. CURVES WITH A NUMBER IN BRACKETS REFER TO THE WATER EXPRESSED FROM THE ROCK SECTION BELOW THE SOURCE ROCK AND ABOVE A MAJOR UNCONFORMITY, THE NUMBER GIVING THE THICKNESS OF THE ROCK SECTION WHEN DEPOSITION OF THE SOURCE ROCK WAS JUST COMPLETE. THE SOURCE ROCK AND BEDS BELOW ARE ASSUMED TO OBEY ATHY'S LAW, BUT THE CURVE S200 (M500) HAS 30% OF NON-COMPACTIBLE BEDS IN THE SERIES BELOW THE SOURCE ROCK. THE NUMBER BEFORE THE BRACKETS SHOWS THE INITIAL THICKNESS OF THE SOURCE ROCK OVERLYING THE COMPACTING BEDS.

overlying the source bed was constant, and that the whole series obeys the same compaction law, the reduced-depth-of-burial scale can be converted to a time scale by assigning a reasonable value to the rate of deposition. On fixing a value for the rate of deposition the reduced-depth-of-burial scale

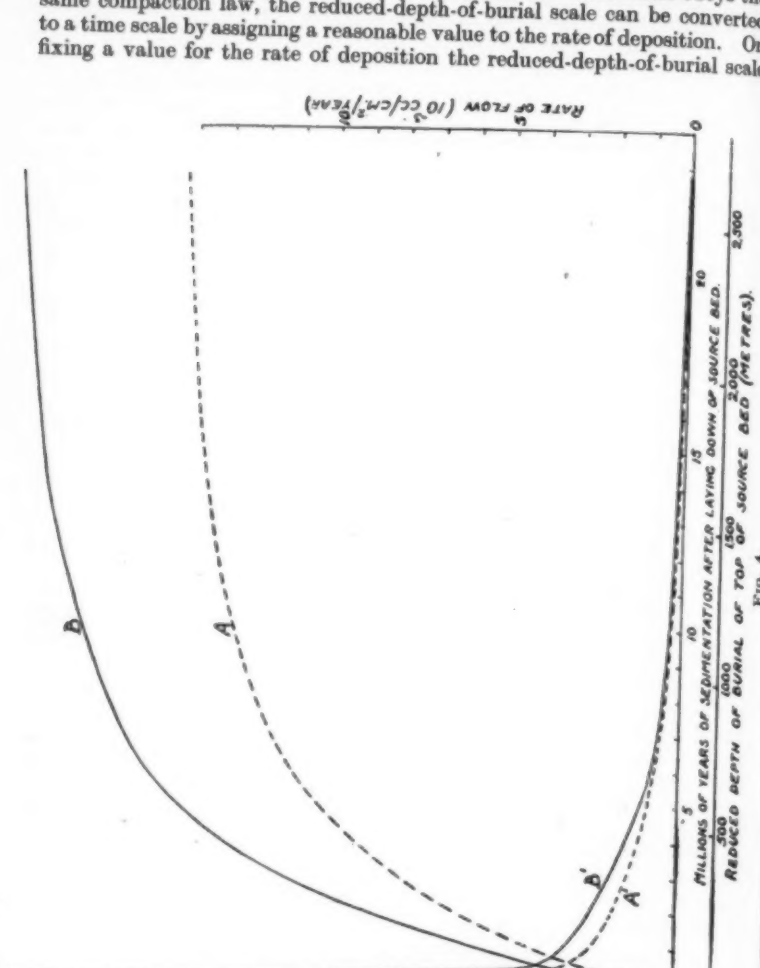
RATE OF FLOW (10^{-3} cc./cm.^{2}/year)
MILLIONS OF YEARS OF SEDIMENTATION AFTER LAYING DOWN OF SOURCE BED.
REDUCED DEPTH OF BURIAL OF TOP OF SOURCE BED (METRES).
TOTAL WATER EXPELLED FROM 1 CM.^{2} PRISM. (cc.)
A
B
A'
B'

FIG. 4.

can be converted directly to a time scale by multiplying throughout by a calculable factor. In Fig. 4 the conversion has been made by using a rate of deposition of 0·02 gm. (weight in water)/cm.^{2}/year. The slope at any point on curve *A* or curve *B* gives the rate of flow across a 1-cm.^{2} section into the bottom or out of the top of the source bed, respectively, at any

time up to the end of deposition, if the bulk of the compaction occurs before deposition ceases. Thus, differentiation of curves A and B gives curves A' and B' which show respectively the bulk rate of flow of water per 1 cm.^{2} into the bottom or out of the top of the source bed. The bulk rate of flow of water into and out of the source bed clearly falls off quite rapidly at first as the depth of burial increases. It is also dependent on the thickness of the source-bed and the thickness of the beds below the source bed; and if much compaction takes place subsequent to the cessation of deposition, the rate of flow derived in the above manner will fall in accuracy, even though correct values may have been assigned to the other quantities about which assumptions have had to be made. The relative values of the rate of flow at different times will carry greater weight than the absolute values, and assuming that the conversion of a depth scale to a time scale has been good, the rates of flow obtained will probably tend, in general, to be maximum values.

It certainly appears that the opportunities for primary migration are, in every way which concerns compaction fluids as the motive power, extremely favourable during the period before the source bed becomes deeply buried. Both the volume of fluid available and its bulk rate of flow decrease as time passes, while the pores diminish in size, thus making primary migration effected by compaction fluids increasingly more difficult, with the consequent implication that oil and gas must migrate, and therefore must be formed, early.

(2) *Closure Developed by Compaction over Buried Hills.*—The reduced depth–true depth curves can also be used to determine the amount of closure to be expected in structures formed by compaction over buried hills. Again, assumptions have to be made about the constitution of the compacting series in terms of compactible and non-compactible sections, but the direction of flow of the compaction fluids is no longer so important, except that locally and temporarily it may affect (increase or decrease) the rate of compaction. All that matters ultimately as regards the form of the beds is that the fluids are lost.

Let there be a hill on the buried landscape rising 200 m. above the general level of the surrounding country (Fig. 5), and let its crest be covered by sediment to a depth of 300 m., with deposition up to 500 m. over the surrounding area, so that the top of the sediment is level at this stage. After deposition of a marker bed, let the thickness of sediment be increased to 800 m. over the crest of the hill and to a maximum of 1000 m. in the surrounding region, *i.e.* at the close of deposition and compaction the surface of the sediment is horizontal. It is required to find the structural closure produced in the marker bed as a result of compaction.

Assuming that the compacting series obeys Athy's law, the reduced depth corresponding with 1000 m. true depth is 744 m.; that corresponding with 500 m. true depth is 327 m. The difference of 417 m. in reduced depth corresponds with the amount of sediment laid on top of the marker bed in the area around the hill, and it is equivalent to 610 m. true depth, *i.e.* the depth of the marker bed after compaction is 610 m. Over the top of the hill 800 m. true depth corresponds with 570 m. reduced depth, and 300 m. true depth corresponds with 181 m. reduced depth. The difference in reduced depth of 389 m., which is equivalent to 575 m. true depth, is the

amount of cover over the marker bed in this region. Hence the closure developed in the marker bed by compaction of the enclosing series is 610 — 575 = 35 m.

The closure determined graphically for the same conditions using Hedberg's law is 22 m., and if the series has 30 per cent. of non-compactible beds, the compactible beds obeying Athy's law, the closure is about 32 m.

Final surface of deposit.
1000 m.
800
600
400
200
0 m.
A. Final position of marker bed if sediments obey Athy's law.
H. Final position of marker bed if sediments obey Hedberg's law.
M. Final position of marker bed if sediments have 30% of non-compactible beds, and the compactible beds obey Athy's law.
Marker bed as deposited
200 m.

Fig. 5.

STRUCTURAL CLOSURE FORMED BY COMPACTION OF BEDS OVER A BURIED HILL.

If the sediment does not attain the level upper surface postulated above, the marker-bed and other beds will have initial dips which will be changed by further deposition and compaction. The changes in the initial dips as a consequence of compaction are still determinable from the curves of Fig. 2.

Peters[1] has given methods for calculating the closure on the basis of Athy's law, methods which depend on the use of the first few terms of the expansions of exponentials as approximations to the values of the exponentials. The present graphical method appears to be of a degree of accuracy adequate to the problem under consideration, and can be applied with equal facility in cases where a mathematical expression is not available for the relationship between depth and porosity.

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THE ANALYSIS OF TRINIDAD CRUDE OILS.*

By F. Morton † and A. R. Richards.†

Summary.

The methods developed in the laboratories of Trinidad Leaseholds, Ltd., for the analysis of crude oils are described in detail. The normal crude-oil evaluation methods have been extended to include detailed analysis of a number of fractions obtained by precise fractionation of the naphtha (F.B.P. 200° C.). The graphical representation of this analysis is shown to be characteristic of the oil, and can be used for the correlation of crude oils, as well as for the detection of minor differences in crude oils produced from the same zone. Details are given of the characteristics of the crude oils from the established producing horizons at the Forest Reserve Field of Trinidad Leaseholds, Ltd.

Introduction.

Trinidad crude oils, as might be expected from the complex geological conditions existing in southern Trinidad,[1] ‡ show marked differences in characteristics.[2] Classified by the method of Lane and Garton,[3] the bulk crude oils fall between intermediate and naphthenic base types.[2] More detailed examination by crude evaluation methods developed in these laboratories [4] shows that this broad classification is incorrect, and that the crude oils vary from the paraffinic oils of Guayaguayare and Tabaquite,[1, 5] to the naphthenic oils of the Forest and Upper Cruse series. Between these extremes lie a number of mixed-base crude oils. In certain areas, notably in the vicinity of the Los Bajos Fault and at Lizard Springs, distillate oils and freak oils of high aromatic content are encountered.[6]

The methods of crude-oil analysis described hereinafter were originally developed to assist in the segregation of crude oils designed to facilitate refinery operations. The detailed naphtha analysis, necessary for the planning of a commercial precise-fractionation programme, proved to be of value in assisting the interpretation of geological data in the areas under examination. The characteristic graphs are used in a somewhat similar manner to the correlation index of Smith [7] or the gravity-interval pattern of Barton,[8] with the additional advantage that they can be used in assessing the value of the naphtha for the production of special products.

Method for Analysis of Crude Oils.

The method developed in the laboratories of Trinidad Leaseholds, Ltd., for the detailed examination of crude oils consists essentially of three separate analyses designated: (*a*) Primary Evaluation, (*b*) Naphtha Characterization, and (*c*) Supplementary Analysis.

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‡ Figures refer to bibliography on pages 73–74.

Primary Evaluation.

A charge of 8 litres of crude oil is blown into the insulated metal stillpot (A, Fig. 1) of 10 litres capacity. Heat is supplied by a hot-plate controlled by a Variac transformer. The stillpot is fitted with a fractionating column packed with 12 inches of 25-mm. Stedman packing.[9] The initial product rate is fixed at about 5 ml. per minute, and the boil-up rate so adjusted that the column operates below flood-point. The heating coil round the column does not supply sufficient heat to maintain adiabatic conditions, and the resultant dephlegmation is used to provide reflux. The reflux ratio thus slowly increases, and product rate slowly decreases as the distillation proceeds. The distillate is collected in bulb B (capacity 4 litres),

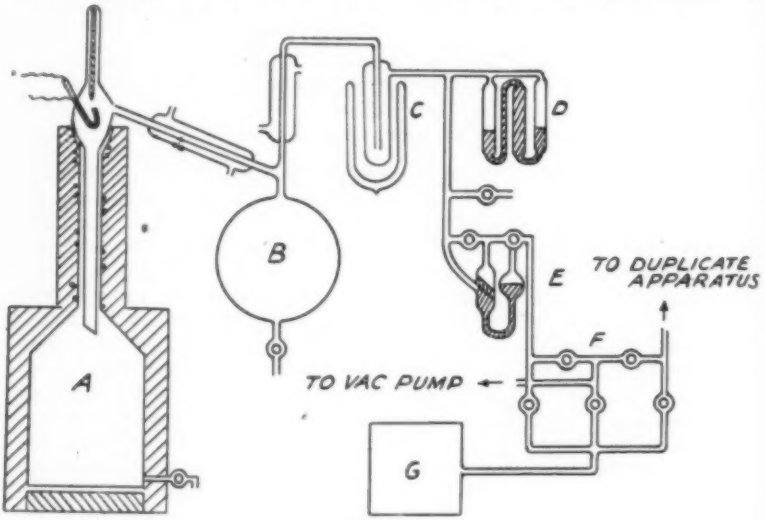

FIG. 1.

and any low-boiling fractions which may escape condensation are trapped in vessel C cooled to − 10° C. by a surrounding medium of solid carbon dioxide in gasoline. When the overhead temperature reaches 100° C. the heat is switched off from the stillpot and column by means of a thermostat, which at that temperature operates a relay opening the heater circuits. By means of hand-switches in these latter circuits, the heaters are prevented from cutting-in again when the temperature falls below 100° C.

The contents of the stillpot are then cooled, the pressure in the apparatus reduced to 15 mm., and the heaters again switched on. The pressure is recorded by the Zimmerli gauge D[10], and controlled by the manostat *E*. This latter is a modified form of that described by Lewis [11] with the replacement of one cylindrical globe by a bulb which removes the necessity of adjustment for each distillation. The entire apparatus consists of duplicate units (Fig. 1), and provision is made for maintaining a pressure of 15 mm. in either one or both units by means of the vessel *G*, previously evacuated

and connected through the stop-cock manifold *F* to whichever apparatus is required.

When the overhead temperature again reaches 100° C. under a pressure of 15 mm., the heaters are switched off by the thermostat control. The heating control circuit is so constructed that a warning light appears when the temperature reaches the prescribed limit.

Naphtha Characterization.

The naphtha fractions obtained in the primary evaluation are blended and dried over anhydrous calcium chloride. 1200–1400 ml. are charged

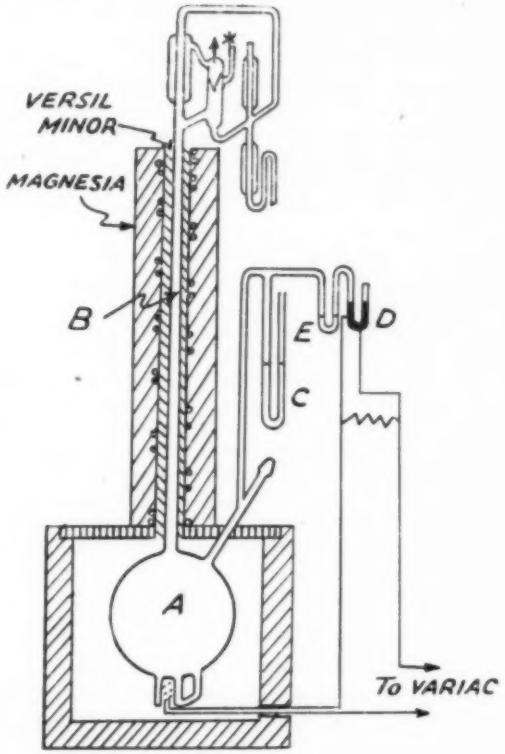

FIG. 2.

SECONDARY STILL.

to the secondary still (Fig. 2), which consists of a 3-litre stillpot fitted with an internal heater and a fractionating column packed with 4 feet of 25-mm. Stedman packing.

A mercury U-tube cut-out *D* is operated by the pressure-drop across the column, but isolated from the vapours by an intermediate glycerine-filled

U-tube *E*. This cut-out is connected in parallel with an auxiliary resistance in the stillpot heater circuit, so that a constant boil-up rate may be automatically maintained throughout the distillation. Adiabatic conditions are maintained by means of a heater wire wound round the pre-formed glass-wool lagging (" Versil Minor "), the precise current required at different top temperatures having been determined by means of calibration experiments with special columns fitted with devices for the measurement of the liquid rate above and below the packing.

In order to assist the maintenance of adiabatic conditions, the conventional hot-plate type heater has been abandoned, and an internal heater of the type shown in Fig. 2 installed. This design avoids the possibility of cracking the charge towards the end of the distillation, since rapid circulation is maintained through the heater by a thermosyphon effect. By this means superheating of the vapours in the stillpot is avoided. It has been found in subsidiary experiments that superheat up to 10 per cent. of the latent heat may be carried by the vapours leaving a conventionally heated pot at the end of a run when the liquid level is low.

The column is fitted with an internal reflux condenser of the minimum hold-up vapour draw-off type,[12] the product being delivered automatically in 10-ml. samples. The distillation is carried out under conditions of maximum boil-up rate with a product draw-off rate of 1 ml. per minute (reflux ratio 20 : 1). Overhead temperature is recorded every 10 ml. (at the point of syphoning). The distillation is continued until the overhead temperature reaches 200° C.

The following physical constants of the so-obtained fractions are determined : Aniline point or minimum equilibrium solution temperature of equal volumes (2 ml.), of aniline and petroleum sample; refractive index, measured at 30° C., since the dew point in these laboratories usually exceeds 23° C.; density, measured by an electro-magnetic densitometer,[13] and mean boiling point. The characteristic graph is then prepared by plotting the physical constants against the fraction expressed as a percentage of the charge to the still. (For convenience the aniline-point scale is inverted.) In later work it has been found advantageous to express the fraction as a percentage of the material taken overhead on the columns thus resulting in a change in the characteristic graph scale. A few of the characteristic graphs reported are of this latter type.

Supplementary Analysis.

(a) *Distribution of Aromatic Hydrocarbons in Naphtha.*

Not more than 500 ml. of the naphtha obtained by the primary distillation are fractionated in a laboratory T.B.P. apparatus, using a fractionating column packed with 1 foot of 25-mm. Stedman packing. The following cuts are taken :—

(*a*) Benzene cut, b.pt. 60–90° C.
(*b*) Toluene cut, b.pt. 90–120° C.
(*c*) " Xylene " cut, b.pt. 120–145° C.

Sufficient of each of these fractions is reserved for aniline-point determination and allowed to stand over anhydrous sodium sulphate. The aromatic material is removed from each of the remaining samples by

shaking with an equal volume of 98 per cent. sulphuric acid for half an hour, care being taken that the temperature of the mixture does not exceed 20° C. After standing and separating, the samples are washed with water and dried. The aniline points of both original and treated samples are then determined consecutively by the same operator using the same aniline stock. The difference in aniline points, Δ, of the two samples is then used to calculate the percentage aromatics, a, by volume by the following formulæ.

(1) For benzene and toluene

$$a = 1{\cdot}13\Delta.$$

(2) For xylene

$$a = 0{\cdot}39\ \Delta.$$

If the percentage aromatics so determined exceeds twenty, the extraction must be repeated.

(b) *Asphaltenes.*

The asphaltene content is determined on the crude oil by the I.P.T. method,[14] using a petroleum ether of slightly modified specification. By rigid adherence to standardized technique reproducible results can be obtained.

(c) *Nitrogen.*

Determinations of the nitrogen content of the crude oil have been made by the method described by Redemann.[15] Unfortunately the nitrogen content of the crude oils does not provide any satisfactory basis of correlation, nor can the nitrogen content of specific fractions or residues be used for this purpose.

Crude Oil Evaluation.

By suitable variation of the primary distillation, evaluation of the yield, quality, and specific properties of naphtha, kerosine, gas oil, and fuel oil residues, etc., can be made. The methods developed for this purpose in the Trinidad laboratories have been described.[4] Recent improvements of these have resulted in methods similar to those described by Mithoff, MacPherson, and Sipos [16] for the characterization of Californian crude oils.

Crude-Oil Correlation.

Correlation of the crude oils is based on the fact that the chemical composition of the naphthas from identical crude oils will be identical, and that differences in the composition of the naphthas must be related to differences in composition, history, and possibly origin of the parent crude oils.

The naphtha fraction is used for this purpose because, as is well known, the lower members of the homologous hydrocarbon series exhibit characteristic differences in physical properties to a marked degree. Extended fractionation studies of the entire crude oil indicate that the differences in the physical constants of the higher-boiling members of the main hydrocarbon series are insufficient for analytical purposes. Furthermore, the complexity of the higher-boiling crude-oil fractions is such as to render impossible, by normal fractionation procedure, the degree of separation necessary for reliable characterization. Since the physical constants of

the individual fractions isolated during the naphtha fractionation will be governed by their chemical nature, it follows that the composite graph picture so obtained will be characteristic of the naphtha examined, and therefore characteristic of the parent crude oil. This composite graph picture of the analysis we have designated the " characteristic graph " of the crude oil. Obviously the characteristic graphs should be reproducible for the same crude oil, and hence it is necessary that standard conditions

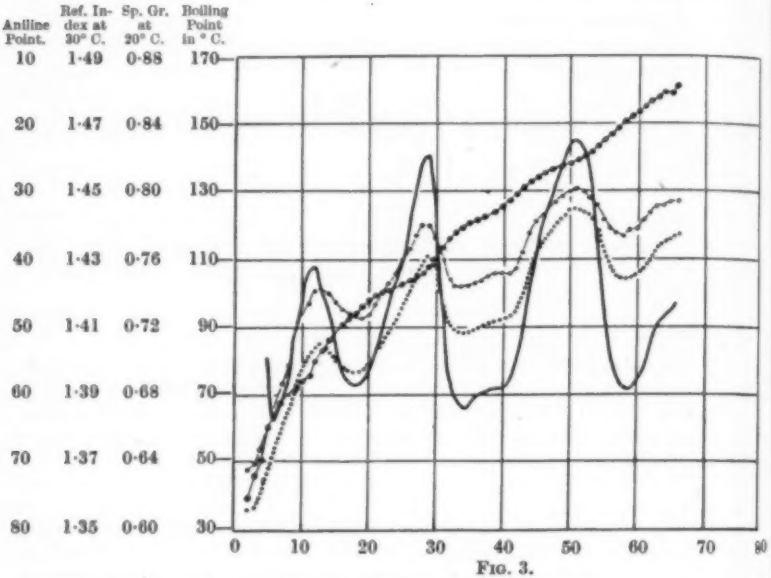

FIG. 3.

The following key applies to all characteristic graphs :

Aniline Points ——————
Ref. Index at 30° C. . . . . .
Spec. Grav. at 20° C. — · — · — · —
Boiling Point in ° C. — ● — ● — ● —

of sampling, analysis, etc., be rigidly observed. The reproducibility of the graphs is illustrated by reference to Figs. 3, 4, and 5. These represent the analysis of the naphtha from three samples of crude oil drawn from the same well, thus checking the sampling procedure as well as the laboratory analytical technique. The same procedure has been repeated in numerous other instances, thus establishing the reliability of the method to indicate identity of crude oils.

Interpretation of the graphs is assisted by the supplementary analysis. The relative amounts of benzene, toluene, and xylene appear to be a characteristic property of the various Trinidad crude oils and, together with the asphaltene content, afford a rapid means of preliminary classification.

Various ratios have been investigated, the simplest method being to express the benzene, toluene, and xylene content as a percentage of the

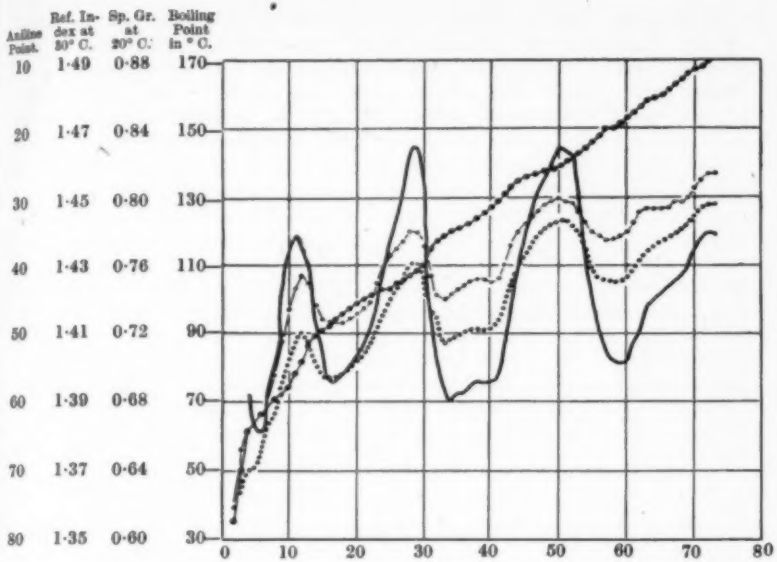
Aniline Point.
Ref. Index at 30° C.
Sp. Gr. at 20° C.
Boiling Point in ° C.
10 1·49 0·88 170
20 1·47 0·84 150
30 1·45 0·80 130
40 1·43 0·76 110
50 1·41 0·72 90
60 1·39 0·68 70
70 1·37 0·64 50
80 1·35 0·60 30
0 10 20 30 40 50 60 70 80

FIG. 4.

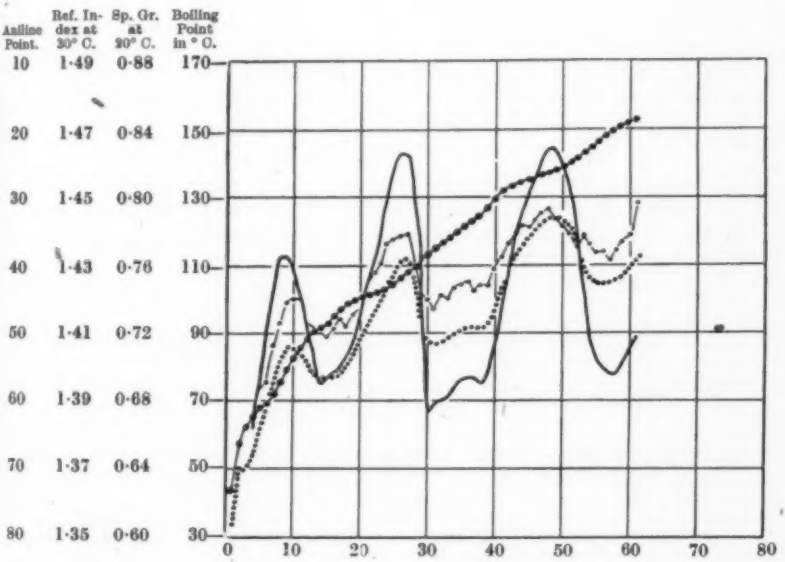
Aniline Point.
Ref. Index at 30° C.
Sp. Gr. at 20° C.
Boiling Point in ° C.
10 1·49 0·88 170
20 1·47 0·84 150
30 1·45 0·80 130
40 1·43 0·76 110
50 1·41 0·72 90
60 1·39 0·68 70
70 1·37 0·64 50
80 1·35 0·60 30
0 10 20 30 40 50 60 70 80

FIG. 5.

material F.B.P. 145° C. (the " B.T.X." figures), and to indicate the sum of these figures as the " total " aromatic content (the A figure). Work on over 150 crude oils from the Forest Reserve field has led to the conclusion that a rough classification into one of several groups may be made on the basis of the B.T.X. figures alone. Whilst this method is of much use in preliminary work, it does not always serve to distinguish between oils of similar, though not identical composition. Among the examples given the Upper Cruse and certain of the Lower Cruse oils are naphthenic in character, and the unusually low aromatic content renders the relation between the B.T.X. figures unreliable. The asphaltene content of these oils, however, shows a marked difference, those of the Upper Cruse containing over 1 per cent. whilst the Lower Cruse oils contain only a trace of these compounds

The preliminary classification is made on the basis of the B.T.X. figures, asphaltene content, and, to a lesser extent, the primary evaluation figures. Subsequent detailed classification is based on a careful study of the characteristic graphs. Where classification by graphs and B.T.X. figures are in agreement, then minor changes in the B.T.X. and asphaltene figures may be taken as significant in the elucidation of geological problems.

Crude Oils of the Forest Reserve Field.

The oils of the Forest Reserve Field are produced from four main horizons, designated as the Forest, the Upper Cruse, the Middle Cruse, and the Lower Cruse Sands. The crude oils analysed from each of the producing horizons were drawn from well-defined limited areas, though not necessarily from the same area for each horizon. The conclusions and inferences drawn from these results therefore apply only within this area, and may be subject to revision on extension of the work. For the following brief description of the producing sands the authors are indebted to Mr. K. W. Barr and Mr. H. C. H. Thomas of the Geological Department of Messrs. Trinidad Leaseholds Limited.

Forest Sands.

A lenticular, often diachronously bedded sandy series, passing upwards into more regularly bedded and extensive sands, unconformably overlain by the Upper Forest Clay. Together with the underlying Lower Forest Clay, these sands form the Forest cycle.

Upper Cruse Sands.

A well-developed and laterally continuous sandy series, representing the last stage of the Cruse cycle. Unconformably overlain by the Lower Forest Clay.

Middle Cruse Sands.

A sand and silt series representing the middle stages of the Cruse cycle.

Lower Cruse Sands.

A sandy series, showing rather variable development, due probably to unconformity. This series represents the concluding stage of the Lower Cruse sub-cycle.

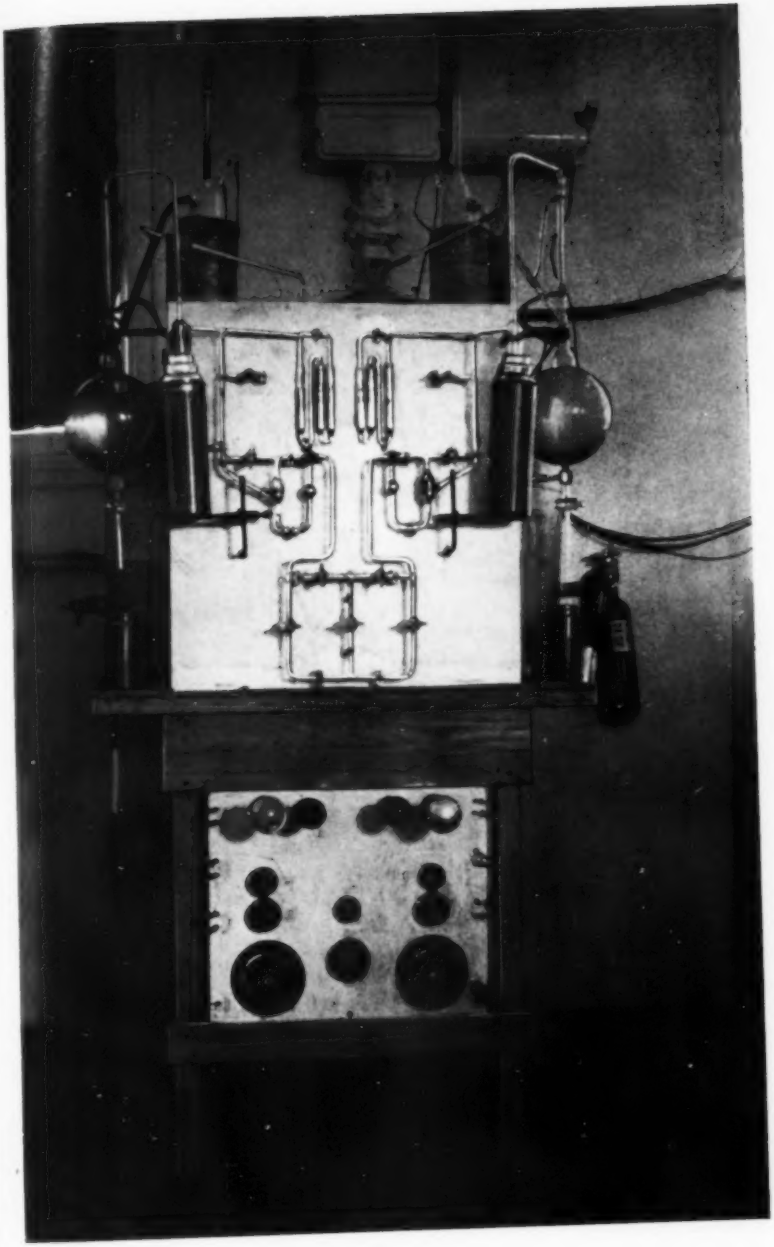

FIG. 6.

[*To face p.* 62.

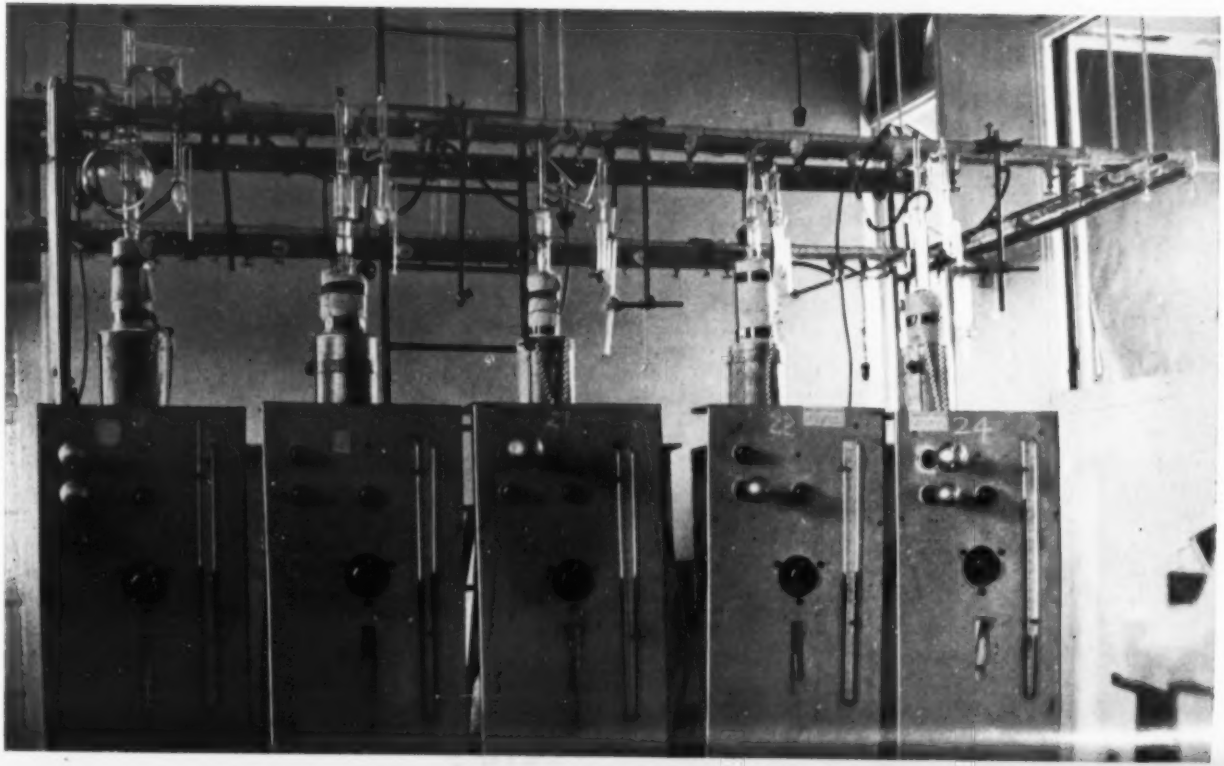

FIG. 22.

FIG. 22.

TABLE I.

Crude Evaluation Data. Forest Reserve Wells.

Column number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Well	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Horizon	F/Sands	F/Sands	F/Sands	Upper	Upper	Upper	Middle	Middle	Middle	Lower	Lower	Lower	Lower	Lower	Lower
Figure number	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Routine Analysis.															
Crude oil :															
Sp. gr. at 60° F. (dry oil)	0·9593	0·9486	0·9357	0·9169	0·9148	0·9212	0·8615	0·8627	—	0·8923	0·8885	0·8822	0·8873	0·8456	0·8413
Gravity, deg. A.P.I. (dry oil)	16·0	17·6	19·7	22·8	23·2	22·1	32·8	32·6	—	27·1	27·8	28·9	28·1	35·9	36·7
Visc. Say. Univ. at 100° F., sec.	558	306	188	138	—	110	40	63	—	42	51	50	48	39	38
Total sulphur, % wt.	1·33	1·22	1·09	1·14	1·45	1·22	0·46	—	—	0·43	0·48	0·55	0·36	0·40	0·36
Distillation of crude oil :															
% Light fractions (F.B.P. 200° C.)	12·0	14·2	18·5	18·0	15·2	18·0	32·1	32·6	33·3	20·5	21·0	25·2	24·7	36·8	33·5
Sp. gr. at 60° F.	0·7914	0·7947	0·7780	0·7710	0·7685	0·7714	0·7624	0·7663	0·7649	0·7786	0·7823	0·7680	0·7709	0·7531	0·7540
Gravity, deg. A.P.I.	46·8	46·6	50·4	52·0	52·8	51·9	54·1	53·2	53·5	50·3	49·5	52·9	52·1	56·3	56·2
% Distilled at 100° F.	3·5	Nil	7·5	18·5	20·0	16·0	18·0	13·0	20·0	6·5	5·0	15·5	13·5	21·5	26·0
% Residue (I.B.P. 200° C.)	88·0	85·8	81·5	82·0	84·8	82·0	67·9	67·4	66·7	79·5	79·0	74·8	75·3	63·2	66·5
Sp. gr. at 60° F.	0·9662	0·9731	0·9680	0·9488	0·9496	0·9531	0·9118	0·9086	0·9149	0·9219	0·9183	0·9223	0·9245	0·9027	0·8913
Gravity, deg. A.P.I.	14·9	13·9	14·7	17·6	17·4	16·9	23·7	24·2	23·2	22·0	22·6	21·9	21·5	25·3	27·3
Flash point (P.-M.), ° F.	192	204	210	208	180	206	206	208	—	216	204	198	200	198	172
Visc. Say. Univ. at 100° F., sec.	700	1400	800	324	312	504	90	—	—	128	112	—	148	76	83
Research Analysis.															
Residue (I.B.P. at 15 mm., ° C.)	200	100	100	200	100	200	100	200	200	100	200	200	200	200	200
% Asphaltenes in residue, by wt.	3·10	1·54	1·20	0·610	1·05	1·43	0·124	0·389	0·194	0·194	0·191	0·325	0·438	0·123	0·143
% Nitrogen in residue, by wt.	—	—	—	—	—	—	—	0·2958	—	—	0·3075	0·676	0·2452	—	—
% Asphaltenes in crude, by wt.	2·62	1·29	1·02	0·500	0·890	1·15	0·098	0·262	0·129	0·154	0·150	0·243	0·328	0·078	0·095
% Nitrogen in crude, by wt.	—	—	—	—	—	—	—	0·1994	—	—	0·2429	0·0506	0·1846	—	—
% Benzene, toluene, and xylene in material, F.B.P. 145° C. :															
B	0·1	0	0·3	0·5	0·1	—	0·4	1·7	—	0·3	0·2	1·3	1·8	1·3	1·5
T	0·4	0·4	0·0	0·6	0·7	—	4·6	6·8	—	1·1	0·2	2·6	3·6	4·6	4·8
X	0·2	0·8	0·6	1·9	2·4	—	7·9	9·5	—	0·6	0·6	4·2	4·6	7·2	7·7
% Aromatics in material F.B.P. 145° C. (A)	0·7	1·2	0·9	3·0	3·2	—	12·9	18·0	—	2·0	1·0	8·1	10·0	13·1	14·0

[*To face p. 63.*

Crude Oils of the Forest Sands.

A number of crude oils from the Forest Sands have been examined. Despite differences in physical appearance the oils examined, with few exceptions, proved to be identical throughout the area under investigation. Crude evaluation data of three typical oils are given in Columns 1, 2, and 3 of Table I, the characteristic graphs being given in Figs. 7, 8, and 9. As will be noted, the characteristic graphs are identical for each of the three naphthas. The aromatic content of the naphthas is extremely low, and throughout the entire boiling range naphthenic

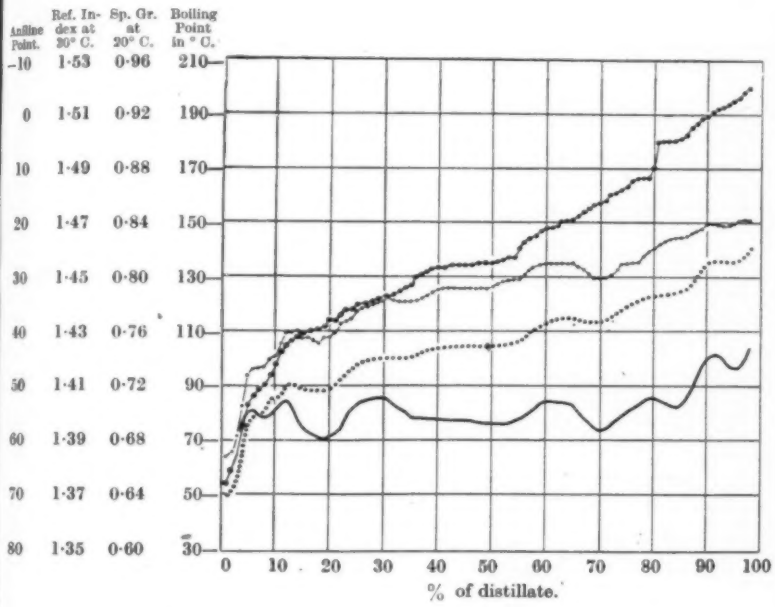

FIG. 7.
WELL A.

hydrocarbons preponderate. The presence of *cyclo*hexane, methyl*cyclo*hexane, dimethyl*cyclo*hexane, and certain trimethyl*cyclo*hexanes can be inferred from the physical constants of the fractions isolated. In subsequent detailed examination of these naphthas [19] only traces of normal paraffins could be isolated, whilst the amount of *cyclo*pentane derivatives was also small. Thus the naphthas fall into group 1 of the naphthenic type as classified by Fenske, Tonberg, and Sweeny.[7] It is interesting to note that by the Bureau of Mines Method [3] the light fractions would be classified as naphthenic. The examination of certain exceptional oils from this area is continuing.

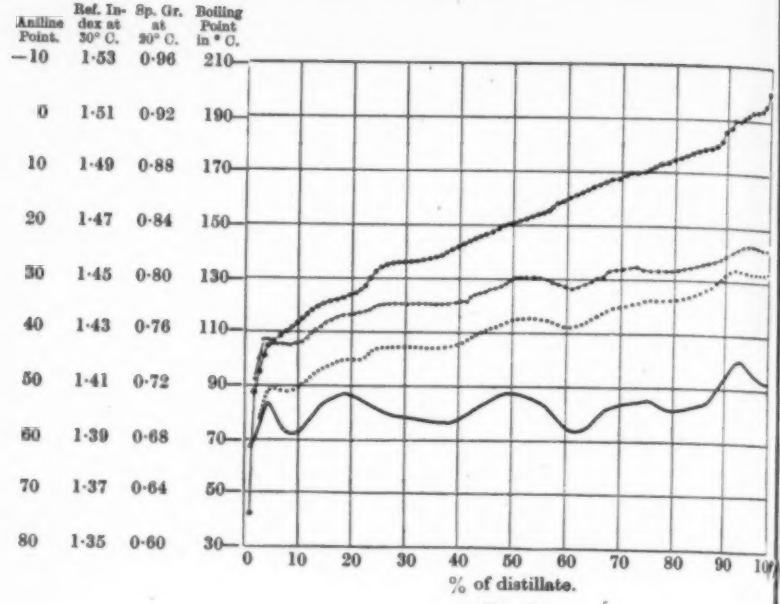

FIG. 8.
WELL B.

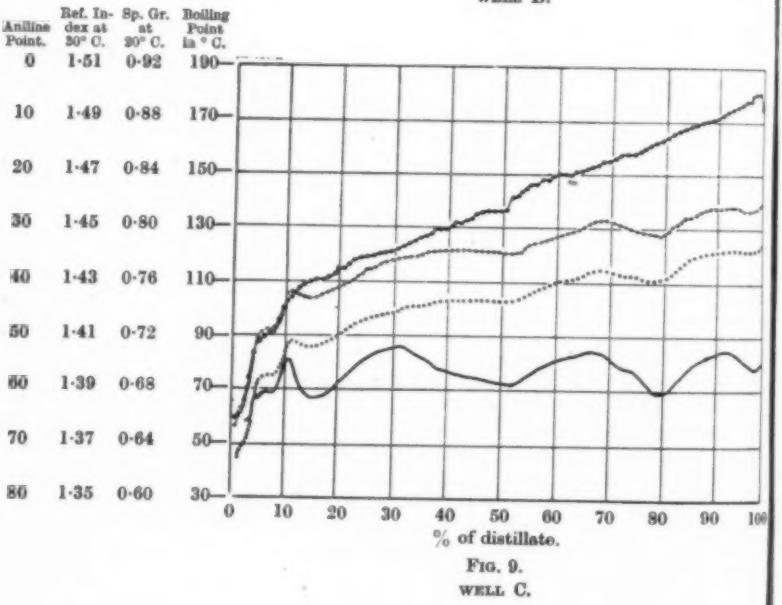

FIG. 9.
WELL C.

Crude Oils of the Upper Cruse Sands.

A number of crude oils from within a strictly limited area of the Upper Cruse Sands have been examined. The original investigation was carried out to assist in a geological examination of the area connected with a study of pressure maintenance. Despite minor differences in crude-oil properties (slight variation in crude-oil gravity, etc., the significance of which is being studied), the oils examined proved to be identical. Crude evaluation data of three oils are given in Columns 4, 5, and 6 of Table I, whilst the corresponding characteristic graphs are given in Figs. 10, 11, and 12, by reference to which it will be noted that naphthas are identical. The

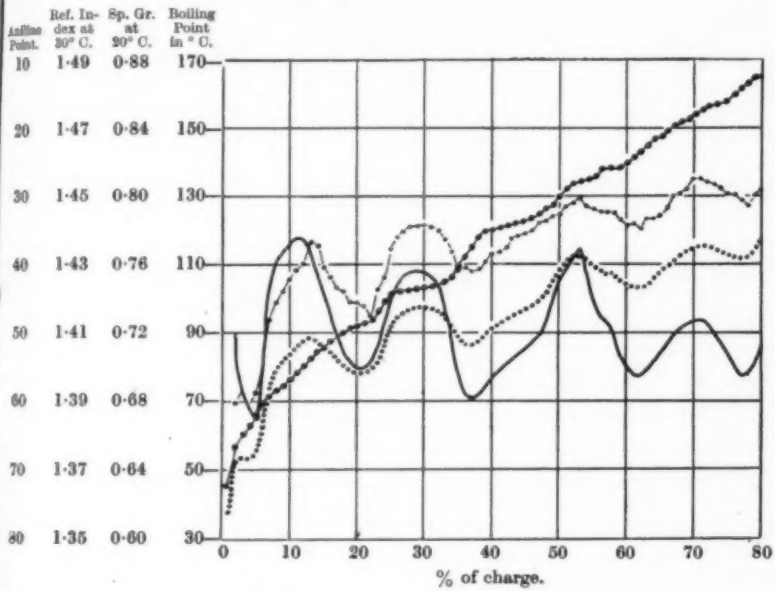

FIG. 10.
WELL D.

aromatic content of the naphthas is low (2–3 per cent.), but slightly greater than the values recorded for the crude oils of the Forest Sands. The presence of small quantities of benzene, toluene, and xylenes is indicated by the physical constants of the fractions and confirmed by the B.T.X. data. Normal paraffins are present only in small amounts, but the presence of certain branched-chain paraffins has been confirmed in the fractions boiling between 85° C. and 95° C. Naphthenic hydrocarbons, however, constitute the main portion of the fractions. The presence of *cyclo*pentane, methyl*cyclo*pentane, *cyclo*hexane, dimethyl*cyclo*pentanes, methyl*cyclo*hexane, dimethyl*cyclo*hexanes, and trimethyl*cyclo*hexanes can be inferred from a study of the characteristic graphs and has been confirmed by subsequent detailed study of the bulk naphtha from this area.[19]

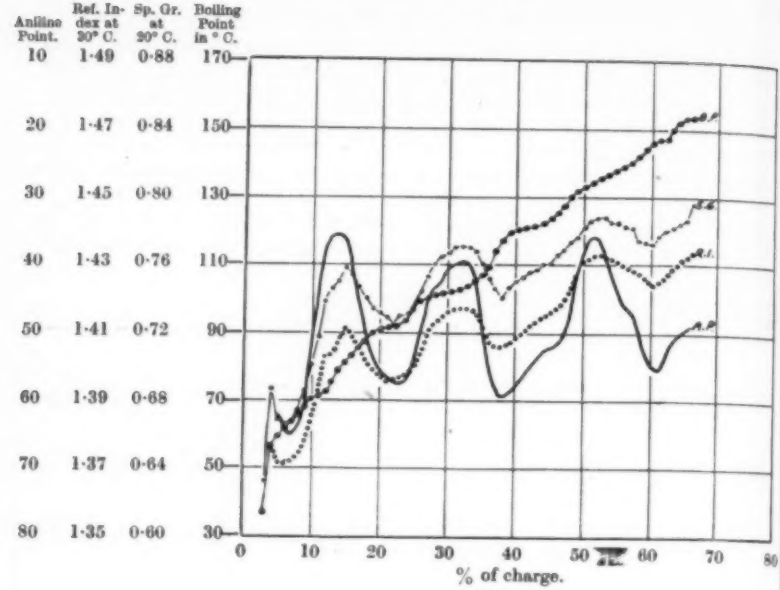

FIG. 11.
WELL E.

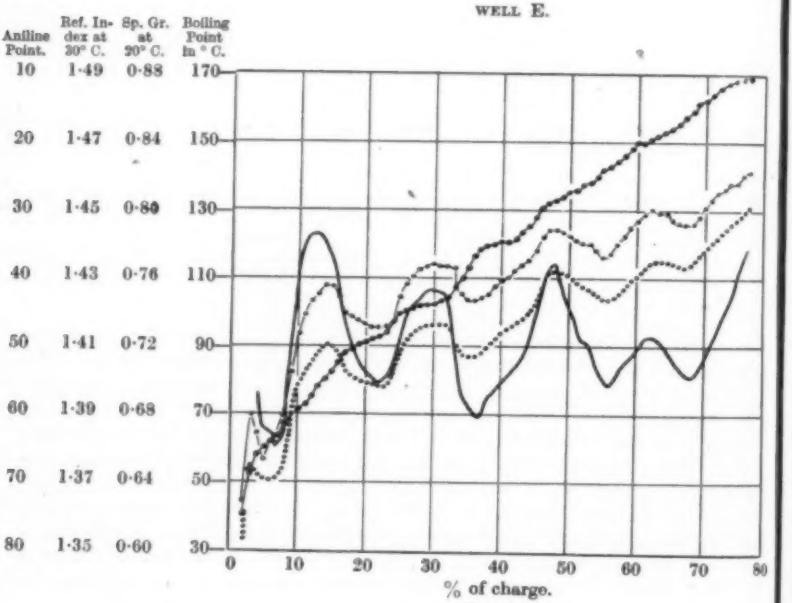

FIG. 12.
WELL F.

Crude Oils of the Middle Cruse Sands.

As might be expected from the nature of the Middle Cruse Sands, the crude oils from this horizon show some variations in physical properties. The analysis of the naphtha, however, indicates the chemical nature of the crude oils from these sands to be identical; three examples are given. The crude evaluation data are given in Columns 7, 8, and 9 of Table I, and the corresponding characteristic graphs in Figs. 13, 14, and 15. The identity of the naphthas is clearly indicated by the characteristic graphs, which further show the presence of quantities of normal paraffins and aromatic hydrocarbons. These graphs should be compared with the

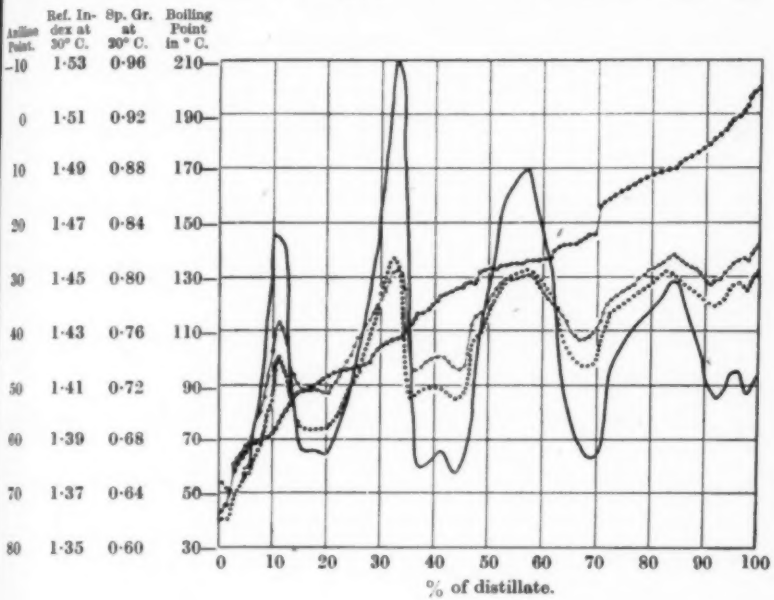

FIG. 13.
WELL G.

refractive-index data given by Fenske, Tonberg, and Sweeny [17] for a Ponca City naphtha. The naphthas contain large amounts of normal paraffins, together with moderate amounts of aromatic and naphthenic hydrocarbons. Both *cyclo*pentane and *cyclo*hexane derivatives have been identified. By methods similar to those used by the A.P.I. Project [6] workers,[18] the presence of the following hydrocarbons has been demonstrated: [19] *n*- and *iso*-pentane, *cyclo*pentane, *n*-hexane, *n*-heptane, *n*-octane, 2- and 3-methylpentane, methyl*cyclo*pentane, *cyclo*hexane, certain dimethylhexanes, methyl*cyclo*hexane, dimethyl*cyclo*hexanes, benzene, toluene, xylenes, mesitylene, pseudocumene, ethyl benzene. Classified by the U.S. Bureau of Mines Method,[3] the light fractions of the Middle Cruse oils are of intermediate type.

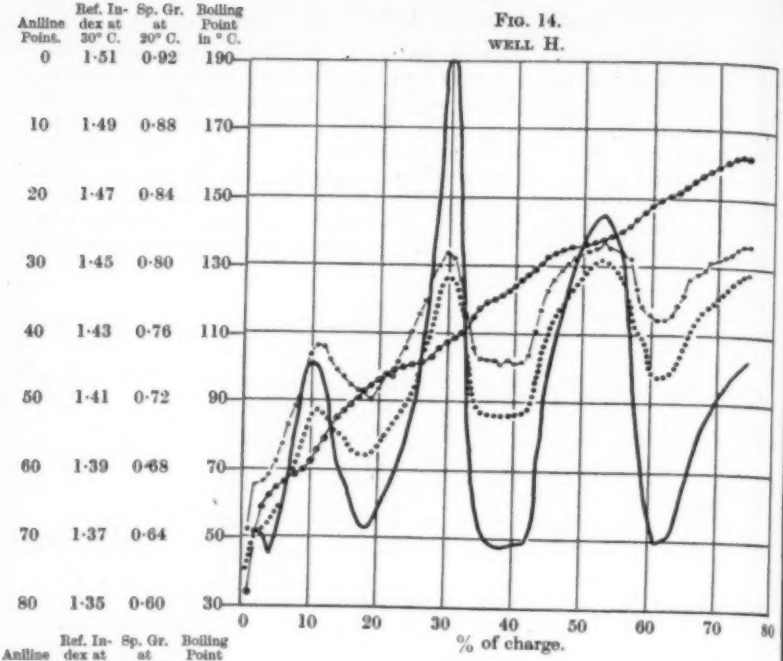

FIG. 14.
WELL H.

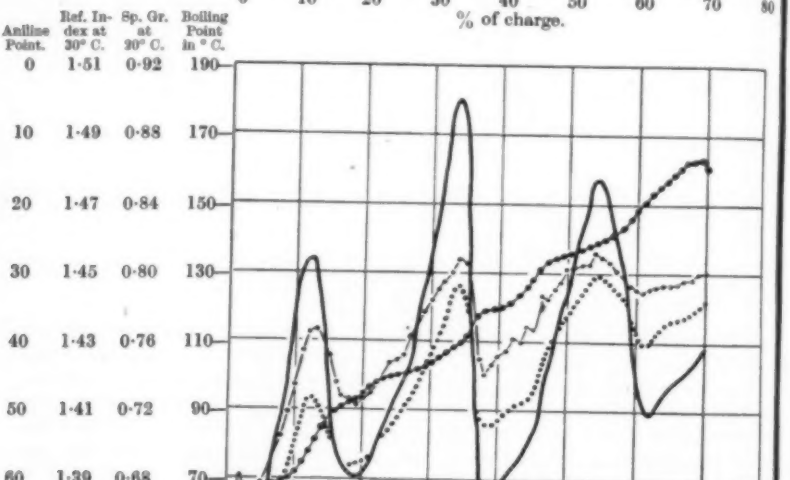

FIG. 15.
WELL I.

Crude Oils of the Lower Cruse Sands.

In order to assist geological work in a section of the Lower Cruse Horizon, a number of crude oils representing the production of the various Lower Cruse Sands have been examined. Unlike the oils of the Forest and Upper Cruse Sands, the Lower Cruse oils examined were of three distinct types, designated as Class I, II, and III. The oils of Class I are definitely naphthenic in character, crude evaluation data being given in Columns 10

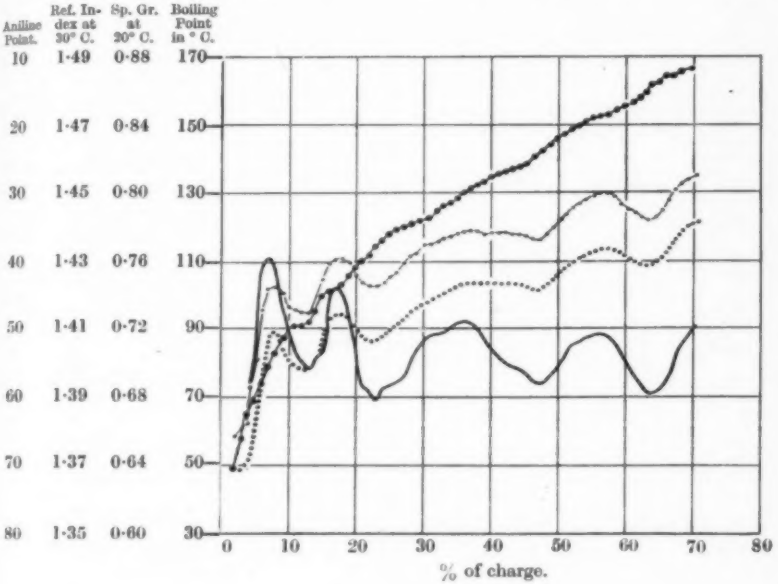

FIG. 16.
WELL J.

and 11 of Table I, whilst the characteristic graphs of these oils are given in Figs 16 and 17. The bulk of the oils examined was of the Class II type illustrated by the oils shown in Columns 12 and 13 (Table I), and Figs. 18 and 19. A small number of the oils were of the Class III type illustrated by the oils shown in Columns 14 and 15 (Table I), and Figs. 20 and 21.

Class I Oils.

The naphthas of the Class I oils are similar to the naphthas of the Forest Sand oils. They are essentially naphthenic, containing only traces of aromatic hydrocarbons, but differ from the naphthas of the Forest Sand oils in containing a greater quantity of material boiling below 100° C. The lower-boiling fractions contain branched-chain hydrocarbons (dimethylpentanes b.pt. 90–91° C.), *cyclo*pentane derivatives, as well as relatively large amounts of *cyclo*hexane and methyl*cyclo*hexane. The oils can be

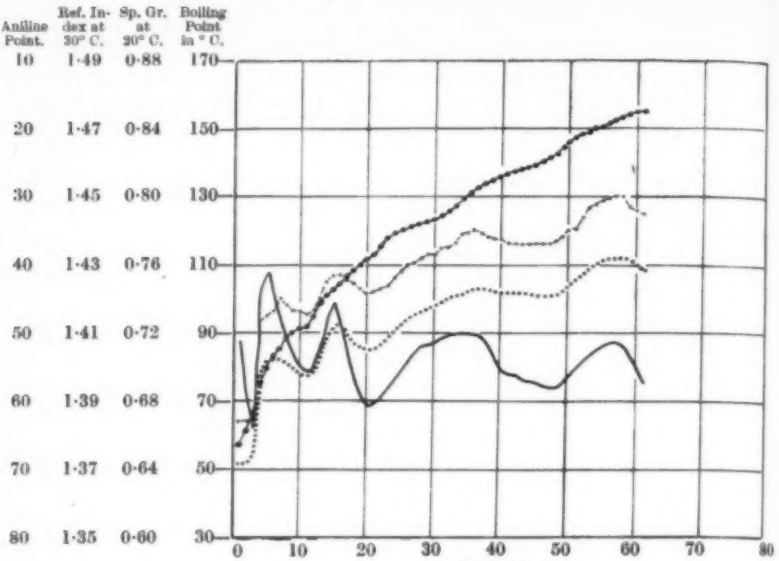

FIG. 17.
WELL K.

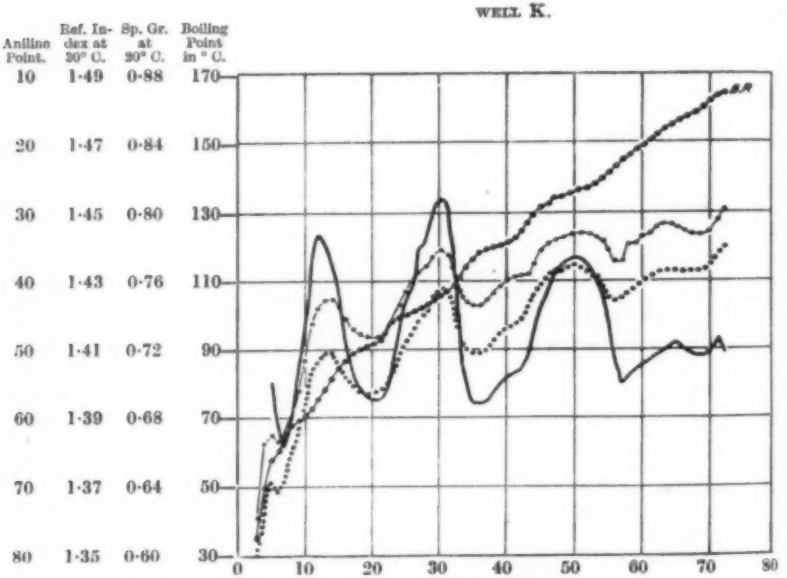

FIG. 18.
WELL L.

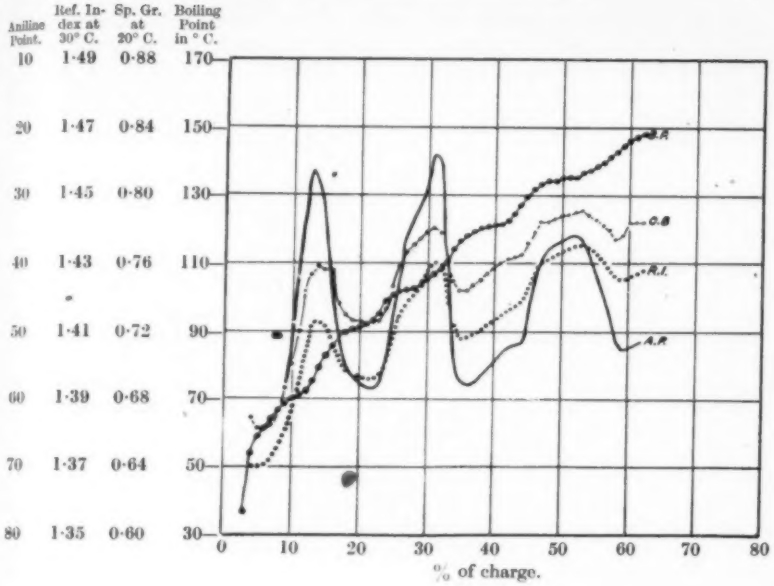

FIG. 19.
WELL M.

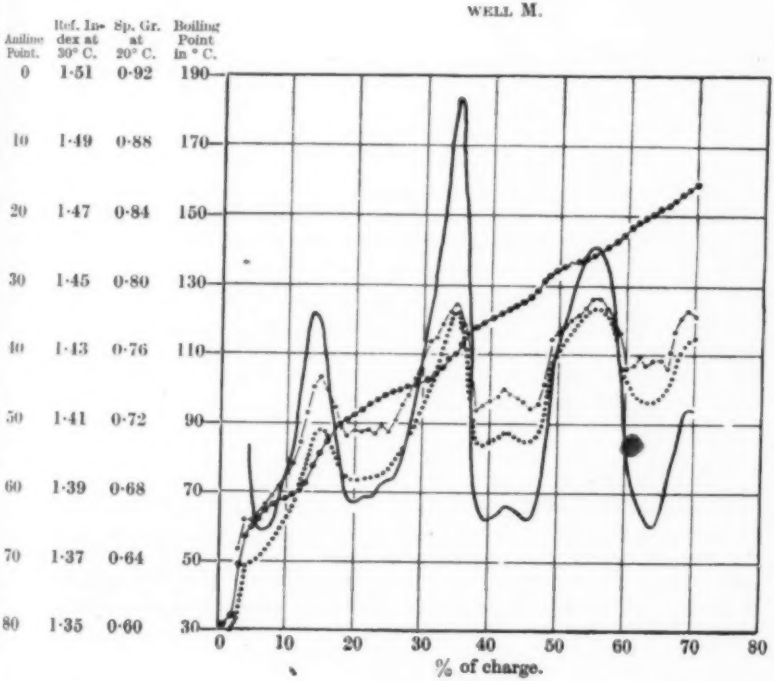

FIG. 20.
WELL N.

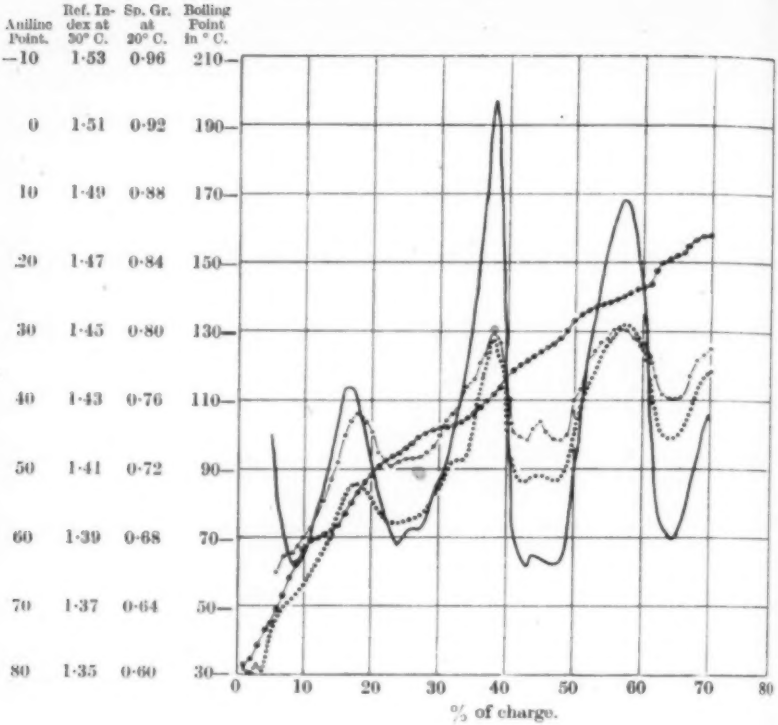

FIG. 21.
WELL O.

differentiated from the oils of the Forest Sands not only by the differences in the characteristic graphs, but also by the asphaltene content of the crude oils.

Class II Oils.

The naphthas of the Class II oils contain moderate amounts of aromatic hydrocarbons, but only small amounts of normal paraffins. *cyclo*Pentane and various substituted derivatives have been identified, as well as a number of branched-chain paraffins.

Class III Oils.

The Class III oils resemble the oils of the Middle Cruse series in that they contain appreciable amounts of normal paraffins and aromatic hydrocarbons. *n*-Pentane, *n*-hexane, and *n*-heptane have been isolated and the presence of *cyclo*hexane, methyl*cyclo*hexane, benzene, toluene, and xylenes has been demonstrated. The crude oils themselves are characterized by high naphtha content coupled with a correspondingly low crude oil gravity.

The bulk of the production from the Lower Cruse Horizon in the area under examination appears to be of the naphthenic type Class II. The oil is probably a mixture consisting of the Class I naphthenic oil with small and varying amounts of the paraffinic type Class III oil. There is some evidence that these oils are grouped within specific areas related to the fault system, and that in certain cases there is a gradual transition from the Class III to the Class II type of oil.

Discussion.

The examination of a large number of crude oils from the Forest Reserve Field indicates that analysis by the methods outlined can be used for the correlation of crude oils. Differences existing between the oils of various horizons are noted. The analysis of one crude oil can be completed in approximately four days. Using duplicate apparatus throughout, from ten to fifteen crude oils can be analysed per week.

Crude-oil surveys of the type outlined are of considerable value in planning refinery operations, and can be used as the basis of a crude-oil segregation programme. The importance of crude-oil segregation has recently been emphasized by Nelson.[20] In the Forest Reserve area, for instance, the crude oils of the Forest, Upper, and Lower Cruse Sands can be bulked as producing naphthenic oils of similar (though not identical) character. In general, the observations of Fenske, Tonberg, and Sweeny [17] concerning the composition of virgin naphthas have been confirmed, more particularly the statement that " contrary to expectations aromatic hydrocarbons are present in low concentrations in naphthenic naphthas." The observations concerning the presence of individual hydrocarbons in the naphthas examined, and the geological applications of the survey will be amplified in future publications.

Acknowledgment.

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